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APRIL 1953

DIVERSION OF LAVA FLOWS AT O SHIMA, JAPAN*

ARNOLD C. MASON AND HELEN L. FOSTER

ABSTRACT. Lava flows during the 1951 eruption of Mihara Yama on O Shima, Japan, were partly blocked by a concrete building on the crater rim. Highly fluid lava filled the interior and poured out through the doors and windows on the opposite side. Observations made on the characteristics of the flows and the effect of this obstruction indicate that it is feasible to construct walls of sufficient strength to divert lava streams from inhabited areas. The pressure from the hydrostatic head of the flow in most cases is small, as it consists of the vertical height of the lava column up to a point of relief which usually is nearby. The impact from momentum may be large, but it can be decreased by locating the wall where it does not face a steep slope, and where there are obstructions above it. Diversion walls should be diagonal to the slope and located topographically to divert the flow to a safe channel.

INTRODUCTION

MIHARA Yama is the active central cone of O Shima Volcano on O Shima, an island 110 kilometers south-southwest of Tokyo, Japan. It has been active repeatedly in historic times, and major eruptions occurred in 1950 and 1951. During 1951 a flow reached a concrete and stone building and was partly blocked by it. Observations made on the characteristics of the flows and the effect of this obstruction suggest principles that might be applied in planning structures to divert lava streams from inhabited areas downslope.

Appreciation is expressed to Gordon A. Macdonald for his critical reading of the manuscript and for his suggestions.

DESCRIPTION OF O SHIMA VOLCANO

O Shima Volcano composes all except a very small part of the island for which it is named. The wooded outer slopes of the volcano rise from the sea and steepen to about 25° near

*Publication authorized by the Director, U. S. Geological Survey.

the caldera rim, or somma. The somma is a circular ridge with a gap on the northeast side. It has a diameter of about 3 kilometers and an altitude of about 580 meters (fig. 1). The barren floor of the caldera within it is about 50 meters lower. Mihara Yama rises in the south part of the caldera and has

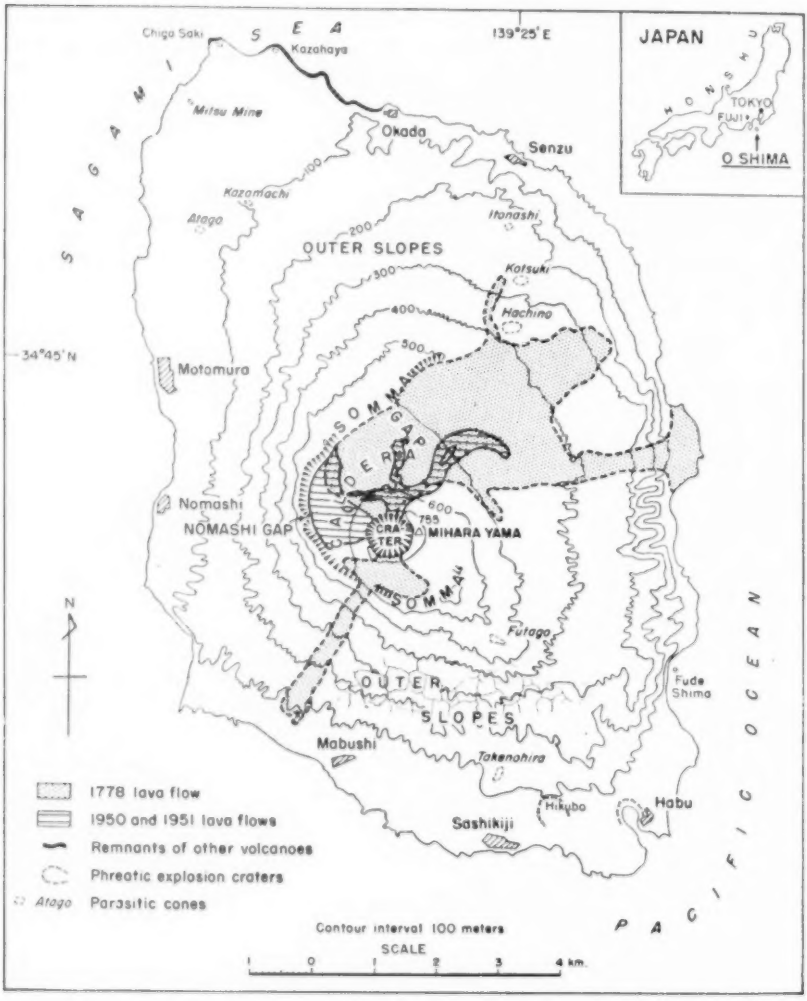

Fig. 1. O Shima and O Shima Volcano. The 1778, 1950, and 1951 lava flows issued from the crater of the central cone, Mihara Yama.

the shape of a truncated cone, the upper slopes of which reach 33° in inclination. Its crest is a crater rim, which has a diameter of 800 meters and ranges in altitude from 675 meters on the north and west sides to 755 meters on the east, the highest point on the island. The enclosed crater has been the locus of all eruptions during historic times. In 1778 a great flow reached the sea and formed a lava delta, but despite the numerous periods of eruption in the interim, no lava overflowed the crater rim again until 1950. The material erupted is basalt.

ERUPTION OF 1950

After 10 years of quiescence, Mihara Yama erupted on July 16, 1950, and was active for more than 2 months. Several cinder cones were built and lava filled the crater and overflowed the rim at four points on the low north and west sides (fig. 2).

ERUPTION OF 1951

Eruption commenced again on February 4, 1951 and continued intermittently for 5 months. Lava overflowed the crater rim in three places. A pond of highly fluid lava, with a temperature above 1200° C. formed in the crater area. When the surface of the pond welled up, the overflow became a torrent of lava 50 meters wide that descended the slopes of Mihara Yama at an estimated speed of 50 kilometers per hour and spread over the caldera floor. The rough surface of the earlier flows that it overran caused the fresh flow to have eddy and other turbulent currents comparable to those in flood waters. Eventually 1.5 square kilometers of the caldera floor became covered with the flows, which were composed largely of jagged, cindery aa lava.

Highly fluid lava was observed to advance rapidly downslope as thin sheets; it had a depth of more than 3 meters only where it accumulated in pools. Cooling, more viscous lava pushed forward more slowly, with aa fronts occasionally as high as 4 meters where the gradient lessened. Continuous flows caused little building up of the total thickness of lava except where the material accumulated in areas of little or no gradient, but pulsating and successive flows caused thickening of the deposits because during the period of lessened flow the lava stream cooled and solidified along the channels of flow.

BLOCKING OF LAVA BY KAKO JAYA

A building known as Kako Jaya (Crater Teahouse) was located on the northwest side of the crater rim. It consisted of a rectangular room about 12 by 8 meters, with its long dimension paralleling the crest on which it stood. It had a

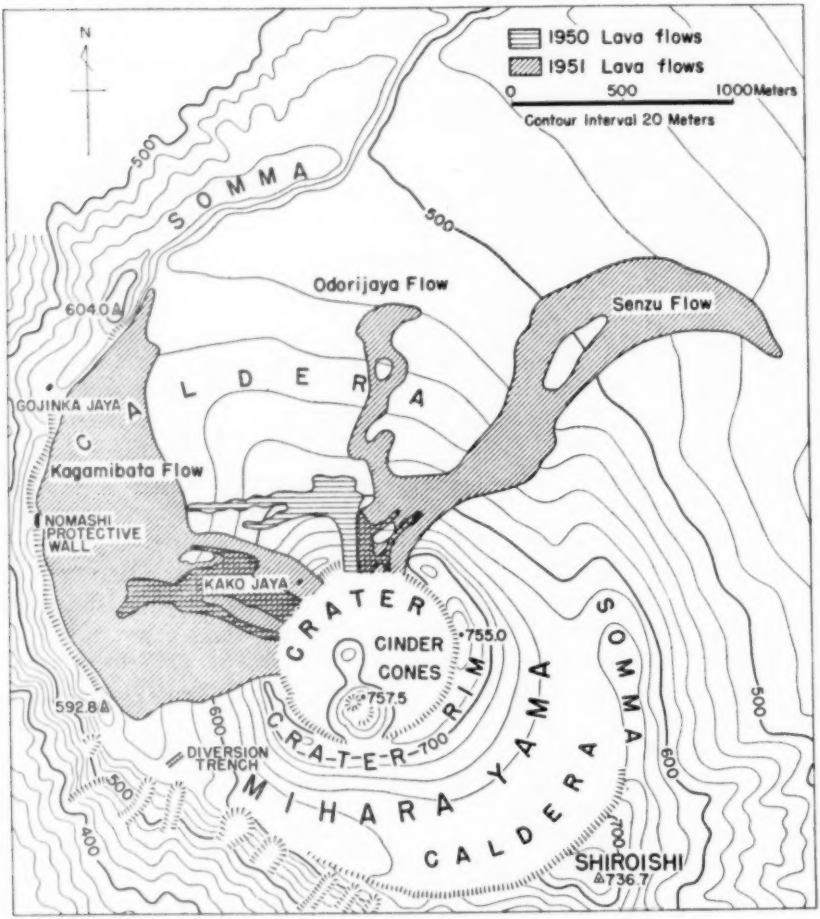

Fig. 2. Mihara Yama on April 20, 1951. The 1951 cinder cone was at its maximum altitude, 757.5 meters, but its height was reduced a few days later by partial collapse. The lava flows advanced no further, although eruption continued intermittently until June 28.

concrete foundation and was constructed of concrete walls about 25 centimeters thick and 3 meters high, faced with mortared lava stone. There were doors on all sides and windows on the long sides. The walls were well constructed and in good condition. The gable roof was supported by wood rafters.

During the 1950 eruption, lava overflowed the crater rim both northeast and southwest of Kako Jaya but not at the building, which was on slightly higher ground. However, on March 9 about one month after the 1951 eruption began, new flows advanced and reached Kako Jaya. The lava ignited the timbers, and the roof and other combustible parts were destroyed (plate 1, fig. 1). The walls resisted the pressure of the lava. The lava entered the building through windows and doors on the long southeast side, nearly filled the interior, and streamed out in small amounts through the doors and windows on the northwest side, hardening in lobate, ropy, pahoehoe form (plate 1, fig. 2). The quantity which passed out through the openings was insufficient to flow more than about 10 meters down the slope (plate 2, fig. 1). In contrast, the slope not in the lee of the building had long flows of lava extending down to the caldera floor (plate 2, fig. 2). When the flow temporarily ceased, the surface of the lava collapsed slightly on the crater side of the teahouse, while the lava held within the room solidified in pahoehoe form. This mass acted as a block to the rise and advance of the next flow, the front of which was broken up in aa form (plate 1, fig. 1).

During the later eruptions in 1951, lava again poured over the crater rim at this location, and eventually the walls of the building became almost completely buried by lava. It could be seen, however, that at least part of them were still standing and had not been pushed over by the lava.

EXAMPLES ELSEWHERE

Blocking or containing of lava by walls has been observed elsewhere. A wall of rubble masonry bounding the three sides of a cemetery adjacent to a destroyed church in Bosco Tre Case on the south slope of Vesuvius confined a tongue of lava which entered from the church side and covered and nearly filled the rectangular area (Jaggar, 1945, plate 1, fig. 1). A similar occurrence was observed about 1911 at Matavanu on Savaii, Samoa (Macdonald, 1951).

On Hawaii, a loosely laid stone wall only a few feet high withstood the tip of the Mauna Iki flow of 1920 and diverted the flow at an angle of about 60° so that it ran parallel to the wall for a distance of 40 feet to a point where the wall was overtopped (Jaggar, 1945, plate 2). Heavy but uncemented stone walls in 1935 confined a lava pool at Humuula, on the northeast side of Mauna Loa, until it rose sufficiently to overflow the walls (Jaggar, 1945, p. 340). In 1950 the second flow of Mauna Loa to reach the sea advanced rapidly down a steep slope but was temporarily stopped by a 4-foot loose stone wall across its course until the lava piled up and spilled over the wall without pushing it over (Macdonald, 1951). In similar manner, on the slope of Mauna Iki, southwest of Kilauea crater, a lava flow was diverted by a small tongue of an older aa flow (Jaggar, 1945, plate 1, fig. 2).

TYPES OF LAVA PRESSURE

Observation of the lava movement against the walls of Kako Jaya demonstrated that the pressure of the flow was not great. Two types of pressure may be exerted on a wall: hydrostatic pressure and pressure from the momentum of a flow. Only the first type affected Kako Jaya. This type of pressure is not great because it consists of little more than the vertical height of the lava column up to some point of relief, which, except in the case of some lava tubes, usually occurs nearby. This pressure may be decreased by diverting the flow, which has the effect of maintaining the point of relief to one side and at a low height.

On a steep slope the second type of pressure can be quite large, especially the momentum of first impact of a fluid material with the specific gravity of lava. This force can be decreased by locating a wall where it does not face a steep slope, by locating it below a forest or below rocky obstructions, by creating obstructions such as rock cairns, and by excavating a moat on the uphill side of the wall to break up the lineal downhill flow. A large, swift stream of lava might not be stopped by a weak wall, but it probably would be stopped by a wall of moderate strength, especially one protected by uphill obstructions. As mentioned above, even a rapidly advancing flow was temporarily stopped by a loose wall on the slope of Mauna Loa in 1950.

OVERRIDING OF WALLS

The accumulation of flows so that walls are eventually overridden by later flows constitutes a difficult problem. For most situations, walls should be designed to divert and not to stop a flow, as lava would soon overtop a wall acting as a dam. To cause diversion, walls need to equal the height of very fluid lava flows, but can be slightly less than the height of cooler flows. Continuous flows cause little accumulation once they become channeled within their own chilled sides and there is some place for the material to move on down a gradient. Pulsating and successive flows permit cooling during periods of lessened flow, and solidification of the lava causes accumulation along the channels of flow. At first this causes succeeding flows to go to one side or the other, but if flows continue, later ones will overrun earlier ones and the general level of the surface will be raised, similar to the growth of an alluvial fan. To provide against this, either higher walls or a series of walls are needed.

DESIGN OF WALLS

Observations made during the eruptions of Mihara Yama indicate that engineering structures can be made that will withstand and divert lava flows. Just as with flood water, the higher and more substantial these structures are, the greater the protection, but even small structures provide some protection.

Walls about 3 meters high should provide protection against most types of flow, but higher walls may be preferable in some places as determined by the cross section of a probable flow. Both sides may be sloped to obtain strength, but the upslope side should be steep enough to prevent overriding of the wall by the momentum of the lava. To enable a wall to divert a flow, and to minimize the liklihood of its being overtopped by an accumulation of lava, a wall should be located in a topographically strategic position and set diagonally to the slope in order to direct the flow into a selected channel wherein little damage will be done. To conduct the flow toward the safe channel, it may also be appropriate to excavate guide channels. Walls should be located below likely vents, but as far upslope as is topographically feasible. In some situations it might be advisable additionally to locate a wall downslope just above the area to be protected, in case of an outbreak at an unusually low point or failure or overtopping of the upslope protection.

Walls with ordinary triangular cross section require approximately four times as much material to build when the height is doubled. Two walls each 1.5 meters high, for example, would require roughly only half the material needed for one wall 3 meters high. If more than one wall is utilized, each should have a topographic position to permit diversion of lava. If the material for the walls were being field-gathered, much less carrying would be required to build two walls. In some cases, as a recourse, two or three inexpensive low walls might be loose-piled to provide partial protection, where an adequate single wall could not be afforded. However, two low walls are not equivalent for the purpose of diversion to one wall twice their height. Chilling of the lava in contact with the ground may raise the level of the bottom of a flow. Because of frictional drag at the bottom, usually the greater part of the movement of material is in the upper half of a flow (Finch, 1943). Hence, the two low walls might both be overtopped by a flow that the high wall would stop.

CONSTRUCTION OF WALLS ELSEWHERE

Walls to provide protection against lava flows have been built on the slopes of Vesuvius. In 1881 a wall was built to try to protect the Waiakea mill near Hilo, but the lava did not quite reach the wall (Macdonald, 1951).

Jaggar early advocated the construction of walls to protect Hilo, and in 1937 made an estimate that a wall just outside the city would cost $400,000, an additional wall at Red Hill to divert lava at a point high up on the slope of Mauna Loa would cost $300,000, and a wall at Humuula Pass to protect the water supply of the city would cost another $100,000 (Jaggar, 1937). In their plan submitted the same year, Win-

PLATE 1

Fig. 1. Interior of east corner of Kako Jaya. The northeast end wall shown in picture was parallel to the direction of movement. Lava from the right overflowed and buried the southeast wall, filled the interior of the building, and poured out through a door and windows on the opposite side. Its surface has a slight gradient from right to left. The solidified mass acted as a block to the next flow, the aa front of which is to the right. View east-northeast.

Fig. 2. Northwest door of Kako Jaya. The concrete wall, 25 centimeters thick and 3 meters high, here faced with mortared lava stones, was adequate to withstand the hydrostatic pressure of the pool of fluid lava within. A small amount of lava escaped through a door, froze with a ropy surface texture, and eventually blocked the exit. View southeast.

PLATE 1

Fig. 1

Fig. 2

PLATE 2

Fig. 1

Fig. 2

Fig. 3

gate, Robertson, and Stephens made an estimate of $1,126,000. In the official report of the District Engineer completed in 1940, an estimate of $2,613,800 was made to construct a wall with a minimum height of 20 feet and a maximum of 68 feet to satisfy the requirements for assured protection (Jaggar, 1945, pp. 345, 350).

THE NOMASHI PROTECTIVE WALL

One wall was built on O Shima to provide protection against lava flows. The village of Nomashi is located below a narrow gap in the west side of the caldera rim. As successive flows from Mihara Yama accumulated in 1951, the lava reached the far side of the caldera and partly ascended the short rise on the inside of the caldera rim. The inhabitants of Nomashi, fearing the advance of the lava, built across the gap a stone wall 15 meters long, 2 to 4 meters high, and 3 meters thick (plate 2, fig. 3; and fig. 2).

As the wall was situated across a gap and not on a slope, it was designed to block the advance of the lava and prevent it from flowing through the gap. The lava would accumulate on the caldera floor, or, before reaching the wall, a part might be diverted by a trench about 8 meters wide which the villagers excavated in the caldera rim at a point 1200 meters to the south-southeast, and nearer Mihara Yama. The trench led to the head of a ravine, which would provide a safe channel down the outer slope of O Shima Volcano.

The lava reached a point within 75 meters of the wall and only 6 meters below it, before eruption ceased. Although the wall was not tested, it is believed that it would have withstood

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PLATE 2

Fig. 1. Northwest wall of Kako Jaya. Lava within the building flowed out through three windows to the right of the door shown in plate 1, figure 2. The small amount of lava that escaped advanced only 10 meters downslope. In contrast, beyond the ends of the house, streams advanced to the bottom of the slope (plate 2, fig. 2). View south-southwest.

Fig. 2. Mihara Yama. Lava overflowed the crater rim and accumulated in the caldera of O Shima Volcano in the foreground. Kako Jaya, located on the rim beneath arrow, blocked the overflow, which resulted in the left of the two small uncovered strips extending down from the rim. Fumes and steam arise from the lava. View is southeast from the caldera rim (somma).

Fig. 3. Nomashi Protective Wall. The village of Nomashi built a wall 15 meters long, 2 to 4 meters high, and 3 meters thick, to prevent lava from flowing through this gap in the caldera rim. The picture is taken from the foot of the nearest lava flow, which reached a point within 75 meters of and only 6 meters below the wall before eruption ceased. View west-southwest.

any flow reaching it. Only if an extremely large volume of lava accumulated in the caldera would the wall have been overtopped. If this became imminent, it might have been possible meanwhile to construct the wall higher. Ironically, the village was nearly totally destroyed by fire 6 months later.

BOMBING OF LAVA FLOWS

Bombing has been utilized in attempts to stop the advance of lava flows. Bombing can be utilized effectively only against lava rivers or tubes, in which the lava has become confined in a channel formed by lava congealing on the margin of the flow (Finch, 1943). The channel acts as a feeder to an advancing tongue of lava. By bombing, the channel may be partly blocked and a breach formed through which the flow may escape. The recommended procedure is to bomb at the lowest effective point, and successively bomb at higher points if the threat of danger continues. In 1935 in the first attempt on Mauna Loa, bombing was directed on the main tubes of a lava flow. In 1942 the practicability of breaking down the levee of an open lava stream by aerial bombing was demonstrated on a flow heading toward Hilo (Finch and Macdonald, 1949).

Bombing has the advantage that the effort is directed to the point of danger and no expenditure is made unless danger threatens. However, a resort to bombing at such a time might be impossible because of weather conditions or poor visibility. Bombing is not effective, but a wall is, against large sheet flows, which often are associated with the beginning or renewal of activity and which may occur suddenly (Jaggar, 1937). Bombing can be utilized in some situations, but it provides no safeguard that is not provided by a wall, and it cannot take the place of diversion walls.

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U. S. Geological Survey
Tokyo, Japan

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THE PARRY ISLANDS FOLDED BELT IN THE CANADIAN ARCTIC ARCHIPELAGO*

Y. O. FORTIER and R. THORSTEINSSON

ABSTRACT. A preliminary description is given of the Parry Islands folded belt in the Canadian Arctic Archipelago. The problems of determining the time of orogeny of this belt and of its relation to folded strata on Ellesmere Island are discussed, and other possible major structural features of the islands are mentioned. It appears that the geological history of the major part of the Archipelago north of latitude 75° N has been more eventful than mere deposition of strata in epicontinental seas over a stable shield.

THE larger part of the Canadian Arctic Archipelago has long been considered as made of sedimentary strata deposited on a stable shield. Haughton's compilation (1857, 1859) of data gathered during the search for Franklin and by earlier explorers has supplied the main basis for such a conclusion. The sequence of exposed formations has been summarily described by many, and lately by Armstrong (1947), as successively younger from southeast to northwest. Folded strata have been known to occur on Ellesmere Island, notably through the observations of Fielden and De Rance (1878), Schei (1903, 1904), and Bentham (1936, 1941). The time of their folding and their southern extension are two problems of interest for students of Arctic geology.

Troelsen, who has been investigating the geology of Ellesmere Island for some time, recently (1950) presented some results of his observations, together with the latest summary of the geology of Ellesmere and adjacent regions. He concludes that marked diastrophism appears to have affected the area at least twice since Precambrian time, and that those periods include close folding at the end of the Silurian or, more likely, some time during the Devonian period (Caledonian-Acadian revolution), and weak folding with local, small-scale overthrusting between Early Jurassic (?) and the time of deposition of Cretaceous or Cenozoic limnic beds. Troelsen thus gives support to those who have believed in the extension to Ellesmere Island, through Spitsbergen and northwest Greenland, of the Caledonian system

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of mountains of northwest Europe. This is in opposition to some geologists who have believed that repeated orogeny in Ellesmere Island had not been proven; or again, in contrast with a third group who think there is some evidence for two periods of orogeny, one in Mesozoic time, but that definite dating of an earlier, pre-Pennsylvanian orogeny must await further investigation.

Folded rocks of Ordovician and Silurian age have been observed on Ellesmere Island as far south as Vendome Fjord and the north coast of Baumann Fjord, where folds trend southwesterly. On the south coast of Baumann Fjord, Bentham (1941) suggests that the folded Ordovician and Silurian strata are buried under flat-lying Devonian and Carboniferous strata. Schei (1904) has measured in the very southwest part of Ellesmere Island some 9000 to 10,000 feet of conformable Ordovician, Silurian, and Devonian strata, gently inclined to the northwest but not folded. He observed undisturbed Carboniferous (Permian ?) beds north of the area of Devonian, but with a gap in outcrop.

Eardley (1948, 1951) has suggested that the folded belt of Ellesmere Island extends through Bathurst and Melville Islands by a westward curving. His arguments are the "substantial thickness" of 3850 feet of Carboniferous (Permian ?) sandstone and shale occurring on the south coast of Melville Island with high dips averaging 65 degrees south, as mentioned by Armstrong (1947), and the coincidence of strike of these with the general contact of the Carboniferous rocks and older strata. This contact, according to the Geological Map of the Dominion of Canada (1945), lies south of Melville and Bathurst Islands, thence trends northeasterly towards southwest Ellesmere Island.

Studies by the Geological Survey of Canada since 1949 show that the group of islands extending from Cornwallis Island westward, through Bathurst and Melville Islands, to Prince Patrick Island, are traversed by a belt of folded rocks, to which the authors refer as the "Parry Islands folded belt." The data have been obtained through the study of air photographs, a flight over the region, field work, and the scanning of earlier explorers' reports. Part of the data have been already incorporated in the Tectonic Map of Canada (1950). The sketch map (fig. 1) of the Canadian Archipelago shows the occurrence

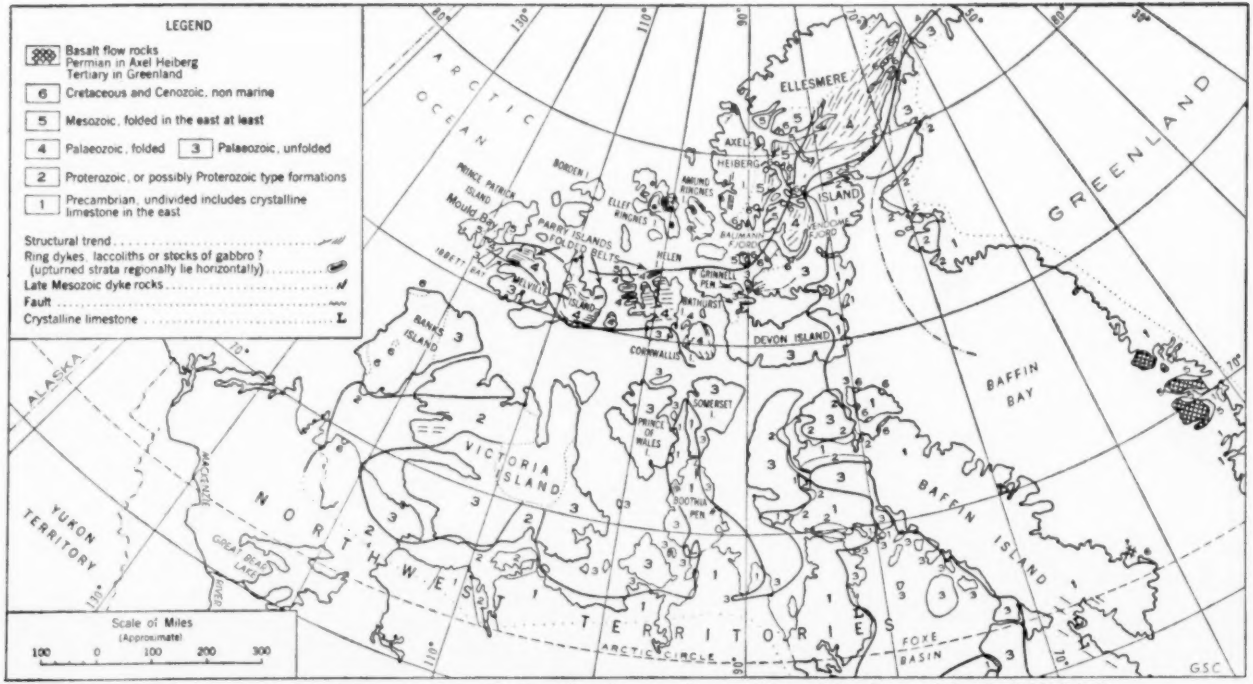

Fig. 1. Geological sketch map of Arctic Canada, showing the position of the Parry Islands folded belt.

of the Parry Islands folded belt. The map and this report must be considered preliminary pending further investigation.

In 1949, Major Ivor Bowen showed to the senior author some air photographs of Bathurst Island, clearly exhibiting folded rocks; he suggested that a geosyncline must have occupied those parts. Further examination of air photographs revealed that the folds on Bathurst Island (plate 1, fig. 1), where they are best displayed within the belt, are open, canoe-shaped structures, apparently without overturning, of Appalachian type. The island has been estimated to have a maximum elevation of some 1500 feet above sea level. In part it has low relief; in other parts it has low rock ridges separated by narrow flat areas and such topographic features are related to the folded structures. This is in contrast with the high relief and the great dissection of the folded belt on Ellesmere Island (plate 1, fig. 2), where the land is 5000 to 6000 feet above sea level in many places (even over 10,000 feet in the northern part), and where crested ridges, with roughly concordant summits, are an expression of the folded strata.

The strata are not markedly folded on the southern part of Bathurst Island, but the folds are well displayed on air photographs on other parts of the island and as far north as Helen Island on latitude 76°40′ N. McMillan (1910, p. 415) reports strata dipping up to 25 degrees southeasterly and northwesterly at Cape Hotspur, well north on the west coast of Bathurst Island, and further south, along the same coast, at Schomberg Point, he observed a syncline one mile in width. Haughton (1857) shows on his map some coal seams trending northeasterly on Bathurst, Melville, and Banks Islands. It now appears possible to us that Haughton may have extended to Melville and Banks Islands southwesterly trends observed only on Bathurst Island coal seams, in an attempt to link reported coal occurrences. The strata on the northeastern part of Banks Island are now known to be horizontal and some of the coal occurrences reported there as well as on the southeastern part of Melville Island may not have been found in situ.

On Melville Island the folds, westerly to southwesterly trending on the east coast, swing to northwesterly in the central part of the island, according to data obtained from air photographs. McMillan's sketch map (1910, p. 449) shows a structural trend north of west in the area of Cape Bounty and Bridport Inlet on

the south coast of the island. His text mentions both northerly and southerly dipping strata, although the section he measured as 3845 feet thick has southerly dipping strata at an estimated average of 65 degrees. McMillan concluded in his summary of structural features that the structure in southern Melville Island was a series of monoclines resulting from block faulting, and that if any folding had taken place it was not apparent. This type of deformation may well have taken place at the edge of the folded belt. McMillan recognized folds on western Bathurst Island but their implication seems to have escaped him, since he failed to mention the role of folding in the general structure of the western islands. In the northwest part of Melville, the folds (plate 2) trend westerly. From air photographs the folds appear closer than on Bathurst, with steeper dipping limbs, narrower crests and sharper noses. No overturning has been detected. The southern boundary of the folded belt is apparently in the vicinity of parallel 75 N in southeastern Melville, and at Ibbett Bay (fig. 1) on the western part of the island. South of this bay, M'Clintock (1855) observed dips up to 5 degrees only. During a flight over the island, the authors observed, within the belt of folded rocks, large areas with strata of gentle inclinations, that may represent younger, unfolded rocks, unconformably overlying older folded beds. The island varies in relief from plains but a few hundred feet above sea level to a western plateau, more than 2000 feet above sea level.

Folded rocks occur on Prince Patrick Island, as observed by the writers both from aircraft and air photographs. However, the areas of distinctly folded rocks are restricted in extent, and there are large tracts of horizontally lying beds that, as on Melville, may represent an unconformable cover of younger strata. The trend of the folded rocks appears to be southerly, suggesting further arching of the folded belt, as on Melville Island. However, air photographs of Borden Island show folds at one locality. Metamorphic rocks have been collected on the northwest coast of Ellesmere Island and there has been speculation as to the western extension of the zone of deformation to which these metamorphic rocks belong. Schei (1904) observed that the folding on Ellesmere Island in latitude 80 degrees north dwindled out westward. He reported volcanic rocks from northernmost Axel Heiberg Island and found similar (p. 462) specimens collected on Ringnes Land. Specimens of basalt from the western part of Ellef Ringnes have been identi-

fied by Fortier, and the writers, while on a flight over the same locality, have observed features suggesting the occurrence of basic igneous rocks. Air photographs indicate similar dark rocks on parts of Prince Patrick. There is much conjecture in all this; nevertheless further investigation may eventually establish the above localities to be within a belt of disturbance, along the very northwest edge of the Canadian Archipelago that is in part covered unconformably by younger, unfolded strata, and joins the Parry Island folded belt on Prince Patrick Island.

Most of Ellef Ringnes is underlain by flat-lying strata, as is presently known from the study of air photographs and a flight over the area. However, the strata have been locally upwarped to form circular structures as described by Brown (1951). From air photographs, such structures (fig. 1) are known to extend from the west coast of Axel Heiberg, through Amund and Effel Ringnes, to Sabine Peninsula, on northern Melville Island. They are presently being investigated in the field by W. W. Heywood. Whether these structures turn out to be due to igneous intrusions or salt doming, they do appear to be another major structural element on what was formerly described by Suess as the horizontally stratified northern border of the shield.

The Parry Islands folded belt may extend beneath the Beaufort Sea to the northeasterly trending Paleozoic beds in the Tanana-Yukon region of Alaska, as suggested by Eardley (1951). However, the northeastern part of Banks Island and the southwestern part of Melville Island do not appear to be within the folded belt. Scrutiny of air photographs has failed to identify folded rocks in that region, which is a plateau of horizontal strata, in part deeply dissected. Porsild (1951) collected Devonian fossils in the northeastern part of Banks Island and did not observe folded strata.

It is interesting to re-examine Haughton's map (1857), which has been, at least up to 1945, the basis for geological maps compiled of parts of the Canadian Arctic. On the Parry Islands, it shows a contact between sandstone on the south and limestone on the north that is parallel, in its major trend, to that of the folded belt as outlined here. A line based on available stratigraphic information, and referred to by Eardley (1951, p. 528), has been sketched on our map (fig. 1). It links

PLATE 1

Fig. 1. Folded strata on the west coast of Bathurst Island. Line across middle ground is photographic flow. (R.C.A.F. photograph.)

Fig. 2. Folded strata on the east coast of Ellesmere Island. (R.C.A.F. photograph.)

PLATE 2

Folded strata on the northwest part of Melville Island. View is to the east. (R.C.A.F. photograph.)

the easternmost exposures of Mesozoic rocks, as reported from Ellesmere Island, with the southernmost exposures of these rocks, as reported from the Parry Islands, that is, on Graham, Table, and Exmouth islands, on a separate island formerly thought to be the northwest corner of Bathurst Island, and on the east coast of Prince Patrick. Although Mesozoic strata are known to be folded on western Ellesmere, those of Graham and Table Islands are apparently flat lying. At present the only significance of the above line is that it represents a linear feature parallel with the major trend of folds on Ellesmere and on the Parry Islands.

Paleontological data from Melville and Bathurst Islands are scant; it is not always clear whether specimens were collected in situ or as float; some identifications are of doubtful nature; and the stratigraphic positions of some identified forms are questionable. Although the above islands are shown on the Geological Map of Canada (1945), as underlain by Carboniferous strata, there is doubt whether the presence of Carboniferous strata has been definitely demonstrated (Armstrong, 1947; Washburn, 1947). The literature contains suggestions that, besides Mesozoic strata, the Permian, Silurian, and even Ordovician are represented on those islands. Thus far, there is no basis to determine the time of orogeny of the Parry Islands folded belt.

The Geological Survey of Canada commenced field investigation of the belt in 1950, when the authors, together with T. Harwood, explored the geology of Cornwallis Island by canoe journey around its coasts. Thorsteinsson is presently engaged in a third field season in those parts.

The coastal region of Cornwallis Island is mainly underlain by limestones and dolomites of Ordovician and Silurian age. A limited area of Devonian occurs along the east coast of the island. One Silurian formation, approximately in the northern half of the island, is more than 5000 feet thick; its graptolitic content is presently the object of study by Thorsteinsson. This formation is in stratigraphic continuity with a shelly limestone to the south. An intercalation of reefy limestone between the two facies has been located along the east coast of Cornwallis Island. The thickness of the Silurian formation so far outlined amounts to some 15,000 feet, and the disposition of the facies suggests a deepening of Silurian sea to the north.

The Silurian facies discussed above can be separated approximately along a line trending somewhat south of westerly. However, the strata are folded, more intensively near faults, in a north-northwest and northwest direction, and appear to link by curving with the easterly trending folds on the mid-latitude east coast of Bathurst Island. The Devonian strata of Cornwallis Island are in conformity with the Silurian strata, and have partaken in the same deformation, so that folding on Cornwallis is as young as Devonian. The observed Devonian strata are made, in their upper part, of coarse clastic sediments, which is somewhat in simile with the Devonian rocks of southwestern Ellesmere Island, where Schei observed these strata to pass upward into a thick sandstone series, but to be unfolded.

Examination of air photographs of northwestern Devon Island, especially Grinnell Peninsula, has brought no light on the relation of the Parry Islands folded belt and the folded rocks of Ellesmere Island. In the eastern part of the peninsula the strata, except for local steepening to some 25 degrees, form a monocline gently dipping to the north. The monocline, which extends to North Kent Island, appears to be the western extension of the monocline of regional extent as observed by Schei (1904) in Ordovician, Silurian and Devonian strata in southwestern Ellesmere. At the northwest tip of Grinnell Peninsula, some inclined strata trend northerly. It is possible that, whereas Cornwallis Island represents a southeastern branch of the Parry Islands folded belt, a northerly branch of the belt escapes detection on air photographs because it is hidden under younger strata in northwesternmost Devon Island, and also in western Ellesmere according to Bentham's (1941) suggestion. This would place the date of orogeny in those parts sometime in the Devonian according to Bentham's observations on Baumann Fjord and those of the writers on Cornwallis Island. It would further imply, if the Parry Islands folded belt as outlined here represent one orogeny, that the Carboniferous and/or Permian fossils collected on those islands were from strata unconformably resting on older folded beds.

Indeed, this communication does not present a solution to already known problems of structural geology in the Canadian Arctic Archipelago. It rather points to further problems and seeks to dispel the former notion of strata laid in epicontinental seas on a shield stable to northwesternmost Arctic lands.

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Ottawa

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GEOMORPHOLOGIC OBSERVATIONS AT THULE, GREENLAND AND RESOLUTE BAY, CORNWALLIS ISLAND, N.W.T.

ROBERT L. NICHOLS

ABSTRACT. The Greenland ice cap at the present time terminates about 12 miles east of Thule, Greenland. In Wisconsin time it probably extended 20 to 30 miles to the west, beyond the present coastline. The marine limit at Thule is approximately 130 feet above sea level. Solution-facetted pebbles, ice furrows, and stone circles are found on the elevated beaches and some of them are buried by solifluction sheets. Solution-facetted pebbles, surface efflorescences, and rainfall records indicate that the climate for a good part of the interval since glaciation has been arid.

The presence of eight extensive, well-planed, smoothed, striated, and weathered outcrops at Resolute Bay, Cornwallis Island proves that the island was glaciated. The marine limit is approximately 545 feet above sea level. Frost mounds, stone polygons, and ice furrows are found on the elevated beaches and permafrost is present two feet below the surface.

INTRODUCTION

DURING the summer of 1948, through the courtesy of the Office of Naval Research, the writer was attached to the U. S. Navy Arctic Task Force 80. These notes are based on five days of field work at Thule, Greenland and five days at Resolute Bay, Cornwallis Island.

The writer wishes to thank Mr. James Crowl, Commander Thomas Fife, Dr. Roman T. Gajda, Major Robert B. Sykes, and Professor Thomas R. Weir who, often at considerable physical inconvenience to themselves, assisted in the field work. Thanks are also due to the officers of the task force for their friendly interest in the work and for their whole-hearted cooperation in landing the writer whenever it was possible. Dr. A. Lincoln Washburn, Arctic Institute of North America, and Mr. Max E. Willard, U. S. Geological Survey, read the manuscript and made valuable suggestions.

THULE, GREENLAND

Dundas Mountain, a prominent mesa close to Thule Village, is about 700 feet above sea level. That it was completely glaciated is proved by the foreign character of the float immediately below the summit of the mountain. An unnamed mountain approximately 1000 feet high, the summit of which is

composed of limestone, is located a few miles south of Thule. Glacially transported schist, granite, and other rocks found within 25 feet of the summit prove that this mountain was completely glaciated. The Greenland ice cap at the present time is about 12 miles east of Thule. The height and location of these glaciated mountains, and the present position of the 600-foot submarine contour line, considered with evidence for eustatic lowering of sea level and depression of this part of Greenland through weight of the ice during Wisconsin time, suggest that the Wisconsin ice cap at its maximum may have extended perhaps 20 or 30 miles beyond the present coast line.

Beach ridges that are excellent in form and in state of preservation, as much as 115 feet above sea level, are found on the peninsula connecting Dundas Mountain with the mainland. A bedrock cliff several scores of feet high is located on the south side of Thule Harbor just south of the delta. On a rock bench of uncertain origin, veneered with several feet of beach gravels and extending inland from the cliff for hundreds of feet, there is a succession of excellent beach ridges, the highest seen being about 125 feet above sea level (fig. 1). The marine limit is 130 feet or more, as ridges at least 5 feet higher are buried by solifluction deposits.

Many of the roundstones in the elevated beaches on the south side of Thule Harbor are composed of fine-grained limestone. Those at the surface have been changed to solution-shaped and solution-facetted pebbles (plate 1). These pebbles have the truncated surfaces, the raised rims, pits, grooves, ridges, and the deposit of travertine on their bottoms which are characteristic of solution-facetted pebbles in arid regions (Bryan, 1929). The solution-facetted pebbles are only one layer deep; immediately below the surface are unmodified beach gravels. Incipient solution-facetting on roundstones is also found on gravel surfaces less than 20 feet above sea level.

The most important factors controlling the time necessary to form solution-facetted pebbles are: (1) the rainfall during the period of their formation; (2) the average temperature of the rainfall and limestone roundstones at the moment of impact; (3) melt water from that part of the snowfall and hail which is not blown away and not evaporated; (4) organic acids formed from vegetation; (5) the chemical and physical characteristics of the limestone. An analysis of these factors

indicates that the Thule solution-facetted pebbles were formed much more slowly than those found in New Mexico (Bryan, 1929), and similar analysis indicates that those at Thule were also formed more slowly than those in Wyoming (Scott, 1947). Bryan (p. 208) and Scott (p. 152) concluded that the solution-facetted pebbles which they studied required thousands of years to form; and a longer period of time must have been required to form the Thule solution-facetted pebbles. This age determination approximates an age based on a rough estimate of the rate of emergence of these beaches (Washburn, 1947, pp. 69-71, 73).

These solution-facetted pebbles indicate, therefore, that for thousands of years the climate of the area has been arid. A

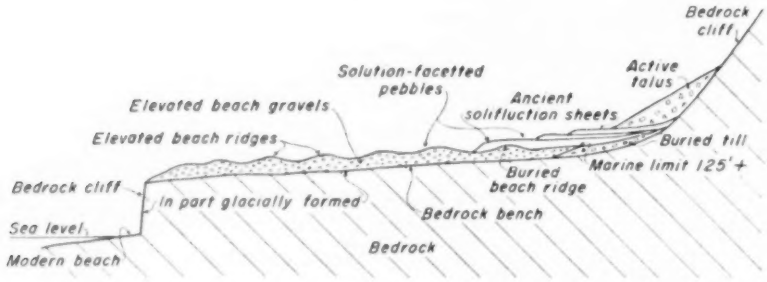

Fig. 1. Diagrammatic cross section showing the elevated beach ridges, solution-facetted pebbles, solifluction sheets, talus, and cliff formed by glacial plucking at Thule, Greenland.

surface efflorescence identified as gypsum by Professor Cornelius S. Hurlbut, Jr. of Harvard University and veins of the same material in soil were seen at one locality. These features also suggest aridity (Twenhofel, 1932, p. 479). The rainfall of Thule at present is about 3 inches a year. It seems probable that something like this degree of aridity has existed for a good part of the interval since deglaciation.

The bedrock bench on which the beach gravels were deposited is not the result of a post-Wisconsin stillstand of the sea at about the elevation of the bench (fig. 1). This is proved by the continuous succession of evenly spaced beach ridges extending from sea level up to 115 feet near the village of Thule, by the apparent absence of this bench in more exposed localities where resistance to wave erosion is presumably similar,

and by the lack of evidence for this stillstand in the Eastern Arctic (Mathiassen, 1933, pp. 71, 97). The bench is either a pre-Wisconsin marine platform, a pre-Wisconsin fluviatile bench, a pre-Wisconsin or Wisconsin glacial bench, or the result of a combination of processes.

The bedrock cliff in front of the bench has not resulted from a stillstand of the sea at about its present level (plate 2, fig. 1). This is proved by the continuous succession of evenly spaced beach ridges not far from the cliff, which extend from sea level to an altitude of 115 feet, and by the lack of evidence for this stillstand in the Eastern Arctic (Mathiassen, pp. 71, 97). High bedrock cliffs are found along the New England coast at Nahant, Massachusetts, and elsewhere. The lack of wave-cut platforms extending seaward in front of them proves, however, that they are not wave-cut. It is the opinion of the writer that the New England cliffs, the one at Thule, and many others seen in the Arctic by the writer are due in part to glacial plucking; by chance the ocean came to rest against them at a later date.

Ice furrows, some of which are hundreds of feet long, 6 or more feet in width, and about 1 foot deep, are found on elevated beaches and on a beach-ridged, elevated delta (Washburn, pp. 102-103). They are in general straight, aligned in all directions, and some cut across beach ridges and abandoned drainage channels (plate 2, fig. 2). Sand and vegetation commonly are found at the bottom, and in the midportions of some furrows are beach pebbles, on end. Some of the furrows are margined by low levees, and commonly they bifurcate and branch at angles up to 90 degrees. On the elevated beaches at the base of Dundas Mountain they run in all directions and outline polygons, some of which are more than 100 feet in diameter.

Excellently formed stone circles were seen at one locality below the marine limit. About 6 feet in diameter, the circles have rock rims which stand almost 1 foot above the flat, clayey, pebbly centers. A group of small, round puddles were formed as the centers of some were covered with water. Stone polygons and circles are not common in the area close to the shoreline, as the surface material is mainly alluvium and beach gravel.

A solifluction sheet covers the higher beach ridges on the bedrock bench. Composed of many individual units, it has a

lobate outer margin which is less than 5 feet high, and its inner margin is being progressively buried by talus (fig. 1). The incipient solution-facetted pebbles found on the surface of the solifluction sheet prove that it is not now active. The sheet was derived from till which veneered the slopes of the mountain in back of the bench. When the supply of till was exhausted, solifluction stopped. This was followed by the formation of talus which is now burying the solifluction sheet just as the solifluction sheet, at an earlier time, buried the beach ridges. The area is a fine example of polygenetic topography as the cliff, beach ridges, solifluction sheet, and talus have all been formed by different processes.

RESOLUTE BAY, CORNWALLIS ISLAND

Eight areas of striated bedrock were found approximately 5 miles east of the landing beach at the head of Resolute Bay. The outcrops, several hundred yards apart, are all found close to mean sea level, and are as much as 100 feet long in the direction of the strike of the striations. The striations are all parallel, and point toward the center of the island. The outcrops are planed level, well smoothed, and weathered. Because of the perfection of the striations, the topography of the area, and the bedrock geology, it is impossible for these striations to have been formed by snow avalanches, river ice, mud flows, or volcanic processes. The length of the striations, their slight obliqueness to the shoreline, the well-planed and smoothed nature of the outcrops, and the fact that the outcrops and striations are weathered, although at sea level, all indicate that fast ice, pack ice, and icebergs were not responsible. It is concluded that the smoothing, planing, and striating were done by glacial ice. The paucity of striations elsewhere is due to the rapidity of weathering and to the presence of thick solifluction deposits and beach gravels.

A lake more than 80 feet deep and less than half a mile in diameter lies at the foot of the bedrock ridge on the east side of Resolute Bay. Its outlet stream has cut a notch at least 10 feet deep and the lake was, therefore, at one time more than 90 feet deep. To the east, the bedrock ridge rises several hundred feet above the level of the lake, and at the west, north, and south sides, the lake appears to be held in by a low, flat, lobate ridge. The available evidence indicates that the lake

PLATE 1

Fig. 1. Solution-facetted and solution-shaped roundstones on an elevated beach at Thule, Greenland.

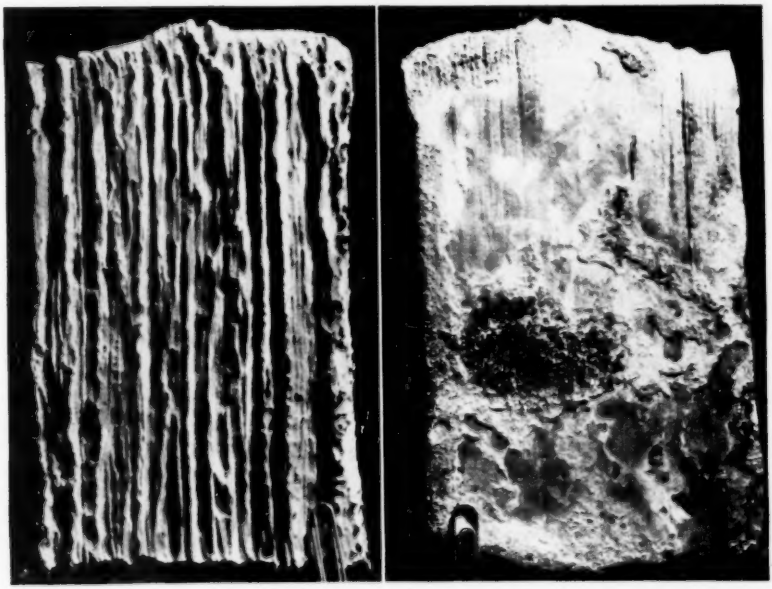

Fig. 2. A, grooved surface formed by solution along bedding planes on the upper side of a beach fragment found on an elevated beach at Thule, Greenland. B, thin veneer of travertine and a very minor amount of solution on the bottom side of the same fragment.

PLATE 2

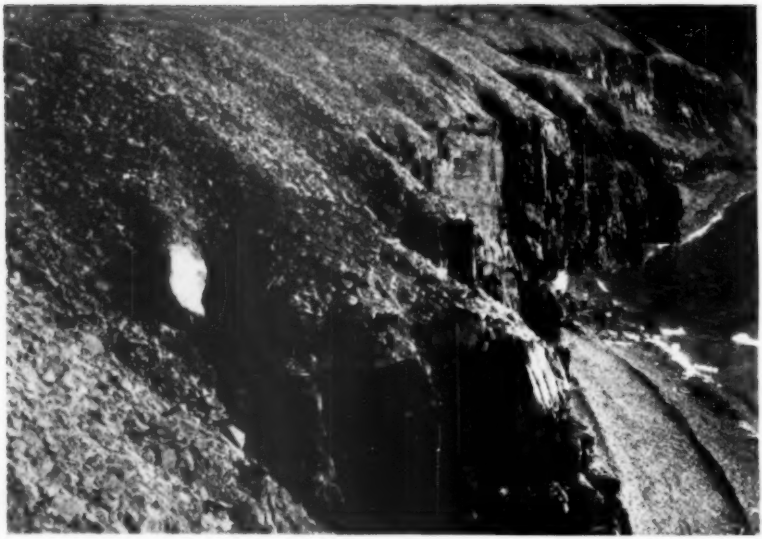

Fig. 1. Elevated beach gravels and a cliff formed by glacial plucking at Thule, Greenland.

Fig. 2. Ice furrow on an elevated delta near Thule, Greenland.

was not formed by mud flows, landslides, or beach deposits and that it is not a sink hole or kettle hole. It can best be explained by glacial erosion and deposition. At least five other lakes are found on Cornwallis Island near the coast.

A 25-mile-long traverse was made inland by helicopter. Along the route taken, the island is mainly a flat plateau several hundred feet in elevation, completely drained by shallow valleys. There are no lakes. It is concluded, mainly on a basis of the striations, that Cornwallis Island was glaciated during the Wisconsin; and the absence of lakes on the plateau suggests that the ice cap was thin. It was probably thicker in the coastal plain area and therefore capable of forming lakes. The fact that ice caps are now found on many of the islands in the Canadian Arctic and that others were glaciated in the Pleistocene supports this conclusion (Washburn, 1947, pp. 44-47).

A barren series of elevated beach ridges and swales is found around Resolute Bay. In places the belt of elevated beach ridges is more than half a mile wide. Using topography, marine shells, and beach deposits as criteria, the marine limit was found to be approximately 545 feet above sea level. Many of the beach roundstones are composed of fossiliferous limestone containing crinoids, brachiopods, corals, gastropods, and other fossils. The beach gravels at the surface are commonly composed of angular fragments, some of which have saw-toothed edges. A few inches below the surface, however, only roundstones are present. The angularity is due to solution and frost action. Numerous boulders of gneiss, granite, diorite, trap, porphyry, garnetiferous rocks, and quartzite resting on beach gravels have been transported by sea ice and icebergs. Marine shells contemporaneous with the elevated beach deposits are very abundant both on the surface and at depth. Age determinations of these shells by the radiocarbon content method might date them and give us data on the rate of emergence (Libby, 1949). Buried whalebone, its presence commonly indicated by moss growing on the overlying gravels, is also present in the elevated beach gravels. Decomposed whalebone is a plant food and moss growth is therefore favored by its presence. The individual beach ridges can be traced for long distances and some of them stand as much as 7 feet above their inner swales. The beach ridges are in general parallel, but in places, owing to irregularities in the pre-beach ridge topogra-

phy, they diverge, and cuspate or lobate ridges are formed. The volume of the beach deposits is great and necessitates as source material the former existence of extensive and thick mantle rock deposits. Glacial till and outwash were undoubtedly important sources, but postglacial solifluction deposits, postglacial offshore marine deposits, and even pre-glacial deposits may also have been reworked by wave action to form the beach deposits.

The beach ridges and swales on the east side of Resolute Bay are crossed by straight lines that obliquely intersect the ridges and swales and form a criss-cross or grid-like pattern. This can best be seen from the air or the deck of a ship. Inspection on the ground reveals that the beach deposits are here thin and that the oblique lines are small buried hogbacks formed of the more resistant bedrock units.

Small ponds are very common in the swales between the ridges. Those adjacent to the present shoreline fluctuate in level and size with the tides, whereas those above the high tide level are more or less uniform in size from day to day. The beach deposits are very permeable and the ponds must be held up by the permafrost and perhaps by till and offshore marine deposits.

Ice-shove ridges and crescents were not seen on the elevated beaches but are common on the modern beach. They are as much as 2 feet high, but are not usually permanent, as the waves destroy them soon after they are formed.

Ice appears to be of little importance in the formation of these northern beaches as they are similar in all respects to those formed in ice-free waters. The presence of icebergs and sea ice ordinarily tends to decrease wave action, but at Resolute Bay neither has been very effective as prominent beach ridges are found up to the marine limit. The formation of ice-shove ridges tends to keep the beach deposits plowed up and overturned and may thus increase the effectiveness of wave action. On the other hand, the presence of ice on the beach protects the beach material and thus decreases the effectiveness of wave action.

The gravels were frozen on August 17th at a depth of 18½ inches beneath the surface of an elevated beach. In general, the top of the frozen gravels is parallel to the slope of the elevated beaches. A thin sheet of meltwater was running down this sloping surface. As additional melting of the frozen gravels

took place after August 17, the active zone in this area is probably about 2 feet thick. The fact that permafrost is found in postglacial fans, deltas, elevated beaches, and in man-made deposits proves that it has been formed in part at least by postglacial and present-day climates.

The beach ridge ponds vary in size with the seasons. The uncovered pond bottoms are soft and muddy, and excellently formed stone polygons are commonly found on them. Stone polygons about 7 feet in diameter outlined by large fragments are found on flat, muddy terrain. Commonly inside these large stone polygons are smaller ones about 1 foot across and outlined by small fragments.

Frost mounds are very common in the swales of the elevated beaches. They are from 1 to more than 3 feet in diameter and are several inches high. Roundstones and fine material are found on their surfaces and they are surrounded by angular fragments usually without interstitial fines. Shells are more common on them than on the surrounding terrain because they are in general composed of finer material. The presence of the roundstones unmodified by solution or frost action proves that the mounds are now being formed. That they have been formed recently is also shown by the fact that some of them rest on a thin soil which had earlier been developed on the beach gravels.

Ice furrows, and the large polygons outlined by them, are very common on the beach deposits and are similar in distribution and characteristics to those found at Thule, Greenland.

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Tufts College
Medford, Mass.

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NATURE AND DYNAMIC INTERPRETATION OF DEFORMATION LAMELLAE IN CALCITE OF THREE MARBLES

FRANCIS J. TURNER

ABSTRACT. The fabrics of three crystalline marbles lacking obvious effects of post-crystalline granulation are described in detail. Particular attention is paid to {01$\bar{1}$2} lamellae optically recognizable as twins. These have restricted ranges of orientation from which it is possible to deduce simple systems of applied stress that could account for observed twinning. The procedure followed in developing this dynamic interpretation of twin lamellae is described. The orientation of *c* axes and that of visible {01$\bar{1}$2} lamellae in grains lacking recognizable twinning can also be explained in terms of the same system of applied stress in any given case. It is concluded that preferred orientation patterns of *c* axes of calcite were determined during the main phase of metamorphism; but visible {01$\bar{1}$2} lamellae reflect a very late phase of incipient deformation. The above dynamic interpretation of natural marble fabric is based on experimental data and on fabrics observed in experimentally deformed marbles.

Most visible lamellae in the three specimens described are parallel to {01$\bar{1}$2}. A few are partings parallel to {10$\bar{1}$1}. No other types of lamellae were recorded.

THE PROBLEM

IN most marbles some grains of calcite show lamellar twinning on {01$\bar{1}$2}, recognizable by differences in optical behavior (notably extinction) between lamellae and host crystal. Examination of a marble section with a universal stage reveals the existence of many other sharply defined lamellae of linear thickness which cannot be identified by optical means as twins. These may possibly be twin lamellae of ultramicroscopic thinness; or they may perhaps be deformation lamellae or partings of another kind. The great majority of such lamellae are strictly parallel to {01$\bar{1}$2}.

Similar {01$\bar{1}$2} lamellae, in some cases demonstrably twinned, are abundantly developed during laboratory deformation of marble, dry or in the presence of water, at confining pressures of 5,000 to 10,000 atmospheres, and at temperatures ranging from 20° to 300° C. Associated with these in particular cases are lamellae {02$\bar{2}$1}, partings {10$\bar{1}$1} and irrationally situated lamellae of other orientations. The nature and significance of the various types of lamellae in artificially deformed marbles is discussed in a paper by Mrs. I. Borg and the writer, now in the press.

The problem raised in the present paper concerns identity and dynamic interpretation of lamellae in calcite of marble in general, in the light of what has been determined in the fabrics of experimentally deformed marbles. For this purpose three calcite marbles have been selected. All are coarsely crystalline and are composed of clear grains with sharply defined boundaries, lacking the marginal granulation, local strain and cloudiness that are so conspicuous in many artificially deformed marble specimens. Their general microscopic appearance suggests that metamorphic deformation has been outlasted by crystallization. In other words the present grain outlines, and presumably the space-lattice orientation pattern of the fabric, appear to have developed under conditions favoring recrystallization; and the crystallization process seems to have continued until and possibly after, the main phase of deformation had ceased. Yet there are sharply defined $\{01\bar{1}2\}$ lamellae in many such grains. These, however obvious they may be on rapid inspection of the section, would seem to be trivial features of the fabric due to minor deformation subsequent to crystallization of the marble. Is there additional evidence supporting this view? If so, are the visible lamellae due to some simple system of imposed stress, or did they form in response to random stresses set up during post-metamorphic cooling and unloading? What is the role of twin-gliding in development of visible lamellae? Are lamellae other than those parallel to $\{01\bar{1}2\}$ present in natural marble fabrics?

One object of this paper is to attempt to answer such questions in the light of experience gained from study of experimentally deformed fabrics. Another is to supply detailed descriptions of natural marble fabrics for general comparison with fabrics of experimentally deformed marbles. Rocks in which post-crystalline deformation seems to have been slight have been selected so as to simplify the problem as much as possible.

BANDED MARBLE, MORAY FIRTH, SCOTLAND

Occurrence and general features of fabric

The specimen, 58M53, is a marble known as the "Boyne limestone" collected at Boyne Bay on the southern shore of Moray Firth in eastern Scotland. It is associated with sedimentary schists which have been metamorphosed at high tem-

peratures and have been folded without strong internal deformation; but within a few hundred yards of this particular locality the whole metamorphic series has undergone intense local deformation along a major zone of dislocation known as the "Boyne line."

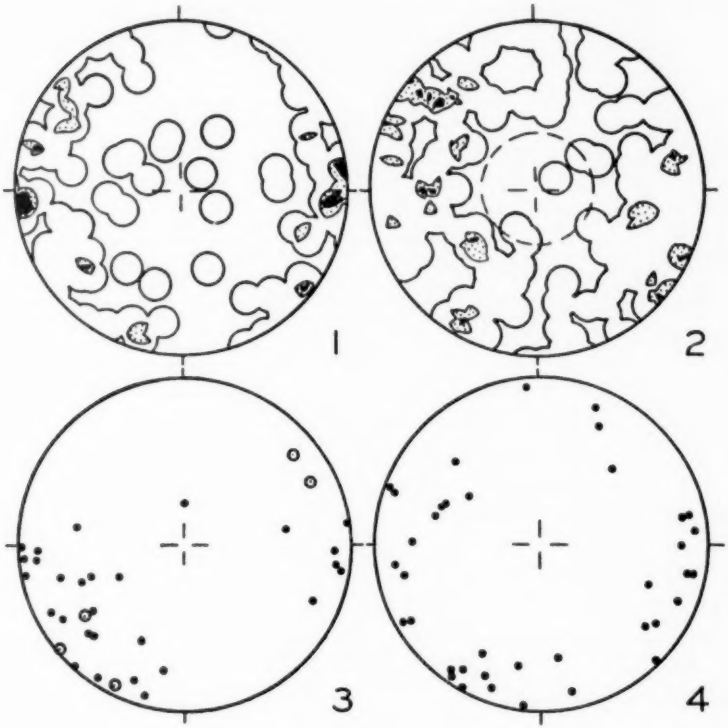
A prominent bedding foliation, S_1 is marked by alternation of bluish micaceous laminae less than 1 mm. thick, and bands 3 mm. to 7 mm. thick composed almost entirely of calcite. The calcite occurs in nearly equant clearcut grains averaging 0.1 to 0.2 mm. in diameter. Many intergranular boundaries are almost straight as seen in sections normal to the schistosity. Most grains show widely spaced sharp lamellae, typically two sets per grain. Individual lamellae in one grain occasionally match corresponding lamellae of closely similar orientation in adjoining grains, and so strengthen the general impression that lamellae are structures of late origin. The diagnostic angle of $26° \pm 2$ between the plotted poles of lamellae and the corresponding *c* axes identifies the great majority of lamellae as being parallel to $\{01\bar{1}2\}$. The only exceptions are rare instances of continuous sharp partings parallel to $\{10\bar{1}1\}$, which closely resemble $\{01\bar{1}2\}$ lamellae in general appearance, and seem to differ from the common discontinuous rather inconspicuous $\{10\bar{1}1\}$ cleavages present in many grains.

Preferred orientation of calcite

Orientation of c axes and $\{01\bar{1}2\}$ *lamellae.*—Figure 1 shows the preferred orientation pattern of *c* axes measured in 75 grains. The degree of preferred orientation is relatively slight. The only consistent feature is a tendency for the *c* axes to intersect the foliation at angles greater than 45°, rather than less than 45°. Within the sector of concentration there is a distinct maximum for axes perpendicular to the foliation.

Figure 2 gives the orientation of 130 prominent sets of $\{01\bar{1}2\}$ lamellae measured in 75 grains. Preferred orientation is by no means strong, especially if allowance is made for existence of a central "blind spot" (inner circle of figure 2) due to inaccessibility of lamellae lying nearly parallel to the section. However it is clear that lamellae on the whole tend to be inclined at angles of less than 50° to the foliation.

Petrofabric analysis of marble from Yule Creek, Colorado, that has been deformed in the laboratory (e.g., Turner and



Figs. 1-4. Boyne marble, 58M53. Orientation of calcite grains. Foliation, S_1, normal to plane of projection, trends vertically.

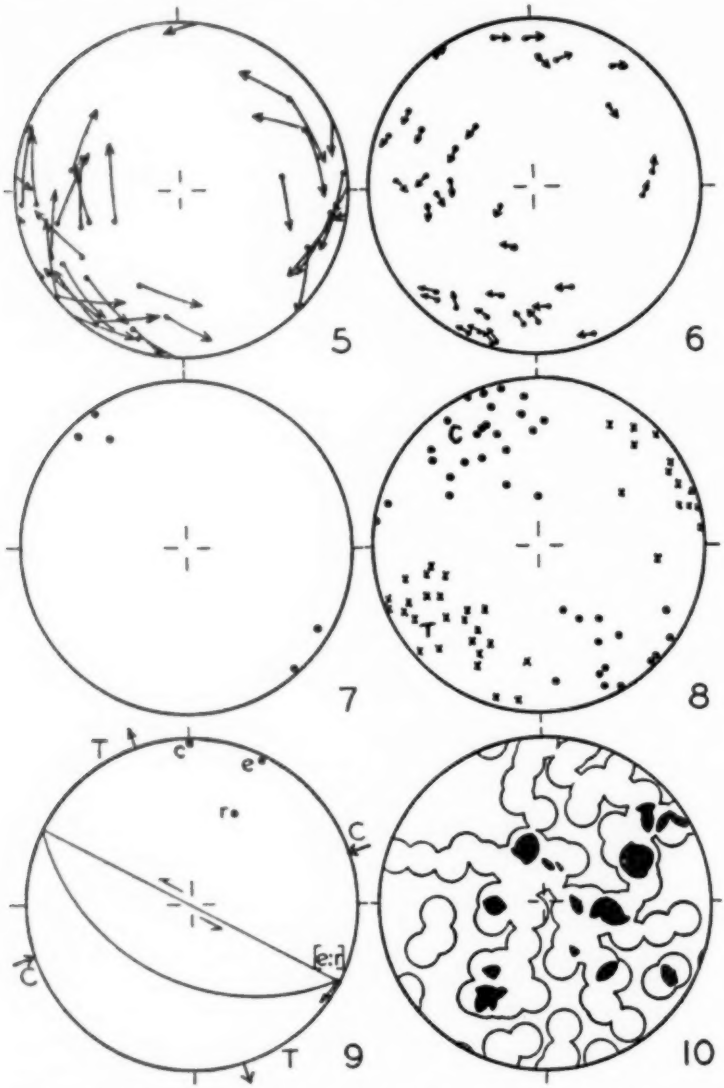
Fig. 1. *c* axes in 75 grains. Contours at 5%, 4%, 1%, per 1% area.

Fig. 2. Poles of prominent $\{01\bar{1}2\}$ lamellae (130 in 75 grains). Contours at 6%, 3%, 0.8%, per 1% area.

Fig. 3. *c* axes in 33 grains with $\{01\bar{1}2\}$ twins. Circled dots represent grains with two sets of twins.

Fig. 4. Poles of 38 $\{01\bar{1}2\}$ twin lamellae (in 33 grains).

Ch'ih, 1951, p. 902) has shown that where the strain is of the order of 10% to 25% elongation or shortening, the edge $[e{:}e']$ between the two best developed sets of $\{01\bar{1}2\}$ lamellae per grain develops strong preferred orientation. In the present rock no such orientation can be observed. The pattern of $[e{:}e']$ edges shown in figure 10 can be explained entirely by the existence of a belt of minimum concentration of *c* axes (fig. 1) necessitating a corresponding belt of concentration of $[e{:}e']$



edges (the angle between c and $[e{:}e']$ in any crystal is about 76°). Lack of significant orientation in figure 10 is only to be expected on the basis of our original assumption that in the Boyne marble visible $\{01\bar{1}2\}$ lamellae are products of a late comparatively trivial deformation.

Orientation phenomena in twinned crystals.—In about 30 per cent of the measured sets of $\{01\bar{1}2\}$ lamellae, twinning can be recognized optically in one or more individuals. The crystals in question—henceforth designated "twinned crystals"—have been considered separately from crystals which lack recognizable twinning of $\{01\bar{1}2\}$ lamellae.

Comparison of figures 3 and 1 demonstrates the sharply restricted range of orientation of *c* axes of twinned crystals. A similarly restricted orientation of twin lamellae (fig. 4) is equally obvious. It would seem likely that twinning has occurred in response to some uniform simple stress that has been imposed upon an aggregate of calcite grains already having the state of preferred orientation of lattice illustrated by figure 1. Those grains suitably oriented in relation to the applied stress have twinned; in other grains obviously twinned lamellae have failed to appear. Three independent lines of evidence collectively lend strong support to this hypothesis:

(1) Figure 5 demonstrates a regular relation in space between *c* axes of similar orientation and twinned $\{01\bar{1}2\}$ lamellae in the same grains. For each grain an arc has been drawn from the *c* axis pole to the pole of the $\{01\bar{1}2\}$ twin lamella. The general direction of departure of arcs from any group of mutually adjacent *c* axes is remarkably uniform.

2) The glide lines—edges $(01\bar{1}2):(10\bar{1}1)$, henceforth designated $[e:r]$— for twin gliding in observed twin lamellae show a high degree of preferred orientation (fig. 6). Moreover the

Figs. 5-10. Boyne marble, 58M53. Orientation of calcite grains. Foliation, S_1, normal to plane of projection, trends vertically (except in fig. 9).

Fig. 5. *c* axes (dots) and poles of $\{01\bar{1}2\}$ twin lamellae (arrow heads) in 27 typical twinned grains. [To avoid confusion from nearly coincident arcs, 6 grains shown in figure 3 have been omitted].

Fig. 6. Glide lines $(01\bar{1}2):(10\bar{1}1)$ in twinned grains of figures 3-5. The arrow is drawn toward the *c* axis in the acute angle of intersection between *c* and the normal to $\{01\bar{1}2\}$.

Fig. 7. Bisectors of acute angles between glide lines $(01\bar{1}2):(10\bar{1}1)$ in 5 grains with two sets of twins each.

Fig. 8. Axes of compression (dots) and tension (crosses) most favoring observed twinning on $\{01\bar{1}2\}$ in individual grains.

Fig. 9. Graphic construction for determining respective axes of tension (T) and compression (C) most favoring twin gliding (in sense of arrows) on a plane $(01\bar{1}2)=e$. Poles of $(01\bar{1}1)=r$, *c* axis, and edge $(01\bar{1}2):(10\bar{1}1)=[e:r]$ are also shown.

Fig. 10. Edges $[e:e']$ between prominent $\{01\bar{1}2\}$ lamellae (twinned or otherwise; 87 in 75 grains). Contours at 3.5%, 1%, per 1% area.

sense as well as the direction of glide lines is generally uniform. This is brought out in figure 6 by drawing from the point representing each glide line an arrow pointing toward the corresponding *c* axis across the acute angle of intersection between *c* and [*e*:*r*]. For this and other details of graphic construction the reader is referred to figure 9. (To construct the glide line [*e*:*r*], align the respective poles of *c* and of the twin lamella *e* upon a great circle of the net; then [*e*:*r*] lies on this great circle at an angular distance of 90° from the pole of *e*.)

(3) The applied stresses that could be most effective in causing twin gliding in a particular $\{01\bar{1}2\}$ lamella lie in the plane containing *c* and the normal to the lamella in question, and are inclined at 45° to the latter (Handin and Griggs, 1951, pp. 866-869, fig. 3). They are respectively: (a) a tension (T in figure 9) applied at an angle of 19° to *c*, measured in the opposite direction to the arc *ce*; or (b) a compression (C in figure 9) applied at 71° to *c*, measured in the same direction as the arc *ce*. The directions T and C have been determined for each case of twinning recorded in the present specimen, and have been plotted to give figure 8. The grouping of both types of direction is strikingly regular. Figure 8 shows that a tensile force applied in the vicinity of T or a compression applied at C, or both forces acting together, could account for all twinning observed in the measured grains. The same forces could also explain absence of recognizable twins in the remaining majority of grains. Note that the arrows of figure 6 must, by the nature of the graphic construction employed (fig. 9), point toward the direction of applied tension and away from that of applied compression.

If a tensile force is applied subparallel to the *c* axis of a calcite crystal, the resolved shear stress coefficient in the direction and sense favoring twin gliding may simultaneously be high on all three $\{01\bar{1}2\}$ planes of the lattice. But if compression is applied so as to induce a high resolved shear stress for the direction of twin gliding on one $\{01\bar{1}2\}$ plane, that for the other two $\{01\bar{1}2\}$ planes of the same lattice must necessarily be low (Handin and Griggs, 1951, fig. 3). Consequently we might expect to find many grains with two, and some with three, sets of twin lamellae in a marble fabric deformed under simple tension; but simple compression should give a fabric

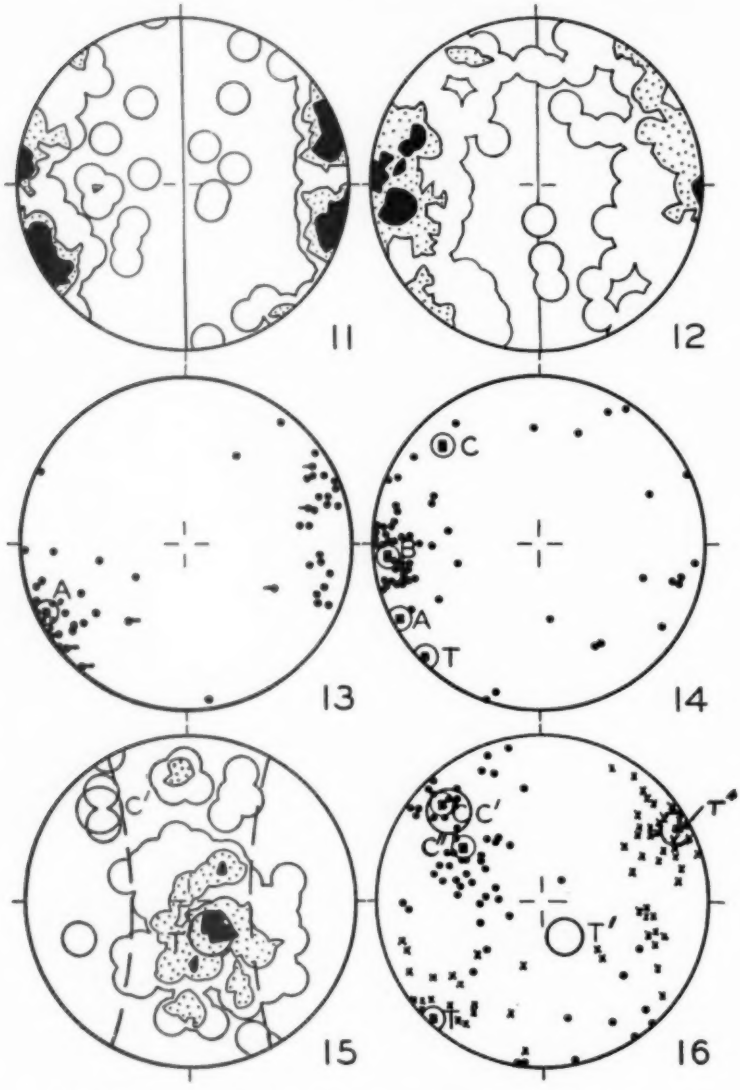
in which most twinned grains have only one set of twin lamellae, only a few have two, and none have three. This second condition corresponds to what has been observed in the Boyne marble 58M53. Only five out of 38 twinned grains show two sets of twins. Moreover if the bisector of the acute angle between the two glide lines is plotted for each of these five grains (fig. 7), it is found consistently to approximate closely the mean direction of applied compression obtained from figure 8.

YULE MARBLE, COLORADO

In an earlier account of the fabric of marble from Yule Creek, Colorado (Turner, 1949, pp. 611-612), attention was drawn to the restricted range of orientation of twin lamellae $\{01\bar{1}2\}$ and of c axes of grains showing definite twinning. This matter is discussed further below in the light of a more detailed examination of a single section of Yule marble (no. 158) cut perpendicular to the foliation. Results of this analysis are strikingly similar to those recorded for the Boyne marble. They are illustrated by figures 11 to 16 and may be summarized as follows:

(1) Orientation diagrams for 100 c axes and for 218 prominent $\{01\bar{1}2\}$ lamellae in the same grains are reproduced as figures 11 and 12. The general concentration of c axes and of $\{01\bar{1}2\}$ poles around the pole of the foliation is typical of the Yule marble fabric as previously recorded (cf. Turner and Ch'ih, 1951, p. 892). This restricted range of lattice orientation restricts the range of possible orientation of $\{01\bar{1}2\}$ twins within the fabric rather more than was the case with the Boyne marble.

(2) In most grains two sets of $\{01\bar{1}2\}$ lamellae are well developed and the third is weak or absent. The edge $[e{:}e']$ between two well-developed sets of lamellae per grain are necessarily concentrated between the broken arcs of figure 15 on account of the strongly preferred orientation of the grain lattices. But within this belt there is strong concentration of edges around the point T′. By analogy with similar patterns recorded for artificially deformed marble (Griggs, Turner, Borg and Sosoka, 1951, fig. 10, p. 1400), that of figure 15 could result from either tension applied in the vicinity of T′ or compression near C′.



(3) In this particular section of Yule marble definite twinning on {01$\bar{1}$2} lamellae is commoner than in most other specimens of the same rock. Some degree of recognizable twinning was recorded for 60 sets of lamellae in 54 grains. The *c* axes

of such grains are shown in figure 13, and the poles of twin lamellae in figure 14. The ranges of orientation are much more restricted than those of figures 11 and 12, respectively.

(4) From the centers of concentration of *c* axes (A) and twin lamella poles (B) for recognizably twinned grains, the respective directions of compression (C) and tension (T) that could account for twinning have been constructed graphically and plotted in figure 14. Similar compression and tension axes have been determined individually for each twinned grain (figure 16). These points are strikingly grouped around centers respectively designated C″ and T″. On the same diagram C and T of figure 14 and C′ and T′ of figure 15 have also been plotted for comparison. The close approximation of C, C′ and C″ is striking. On the other hand T′ (deduced from orientation of edges [*e*:*e*′] is far removed from T and T″. Orientation of twin lamellae and *c* axes of grains in which they occur can thus be explained satisfactorily by assuming a late compression applied in the vicinity of C′, or a tension applied near T. But only the compression can explain the orientation of [*e*:*e*′] edges as determined for all prominent {01$\bar{1}$2} lamellae (twinned and otherwise).

Figs. 11-16. Yule marble (No. 158; not experimentally deformed). Orientation of calcite. Foliation is normal to plane of projection and trends vertically.

Fig. 11. *c* axes in 100 grains. Contours at 5%, 3%, 1%, per 1% area.

Fig. 12. Poles of prominent {01$\bar{1}$2} lamellae (218 in 100 grains). Contours at 4%, 2.5%, 0.5%, per 1% area.

Fig. 13. *c* axes of 54 grains (out of 100) with {01$\bar{1}$2} twins. Points with horizontal bar represent grains with two sets of twin lamellae. A = center of concentration of *c* axes.

Fig. 14. Poles of 60 {01$\bar{1}$2} twin lamellae (in 54 out of 100 grains). A = center of concentration of *c* axes (fig. 13); B = center of concentration of lamella poles; C and T are respective axes of compression and tension constructed from A and B.

Fig. 15. Edges [*e*:*e*′] between prominent {01$\bar{1}$2} lamellae (twinned or otherwise; 105 in 100 grains). T′ and C′ are respective axes of tension and compression that could account for the orientation of [*e*:*e*′].

Fig. 16. Axes of compression (dots) and tension (crosses) most favoring observed twinning on {01$\bar{1}$2} in individual grains. C and T as in figure 14; C′ and T′ as in figure 15; C″ and T″ are respective centers of concentration of individual compression axes (dots) and tension axes (crosses).

(5) Finally the glide lines determined for individual $\{01\bar{1}2\}$ twin lamellae are plotted in figure 17. Because of the strong preferred orientation of *c* axes (figure 11), edges of the $[e{:}e']$ type must be concentrated within the belt bounded by the arcs LL and MM (since such edges intersect the *c* axis at 64°). The glide lines of figure 17 are concentrated within a sector of this belt such that they also make angles of between 30° and 60° with the axis of assumed compression C″ of figure 16. Note how both the direction of applied stress and the initial state of orientation of the grain lattices determine the pattern of the glide-line diagram.

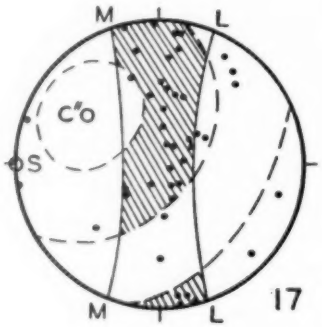


Fig. 17. Calcité of Yule marble (No. 158). Orientation of projection, as in figures 11-16. Glide lines $(01\bar{1}2){:}(10\bar{1}1)$ in twinned grains of figures 13, 14. C″ is the center of compression as in figure 16. Broken arcs represent small circles about C″ at angular distances of 30° and 60°. Full arcs LL, MM represent a small circle about S (pole of foliation) at 70° from S. The overlapping area is shaded.

FOLIATED MARBLE, SONORA, CALIFORNIA

Field data

The specimen (55M50) was collected from a thin bed of marble interstratified with low grade schists which outcrop on California state highway 108 immediately east of the town of Sonora. These rocks form part of the "bed-rock series" of the Sierra Nevada western foothills region, and trend approximately parallel to a contact with intrusive granodiorite not far east of the outcrops under consideration (Heyl and Wiese, 1949). Foliation, parallel to bedding, is vertical and strikes N20°W. A prominent lineation in the schists, due to intersection of sur-

faces of strain-slip with the principal foliation, plunges S20°E at 45°. No corresponding lineation is seen in the marble; and foliation, too, is less conspicuous than in the schists.

General character of marble fabric

Examination of an oriented specimen (with several faces roughly polished) and of three mutually perpendicular oriented micro-sections reveals the following elements in the marble fabric (fig. 18):

S_1 = bedding and foliation; strike N20°W, dip vertical; marked by rough fissility of the specimen and by alternation of coarse white and very thin fine-grained gray bands.

S_2 = roughly parallel slip surfaces slightly displacing S_1; marked microscopically by parallel alignment of elongated grains in local bands a fraction of a millimeter thick. Strike S45°E; dip 70° to SW (determined by plotting on a projection net the traces of S_2 on variously oriented sections).

L_1 = irregular lineation, due to slight small-scale undulation of S_1.

J_1 = joints striking N70°E, dipping 38° to SSE.

J_2 = joints striking N70°E, dipping 58° to NNW.

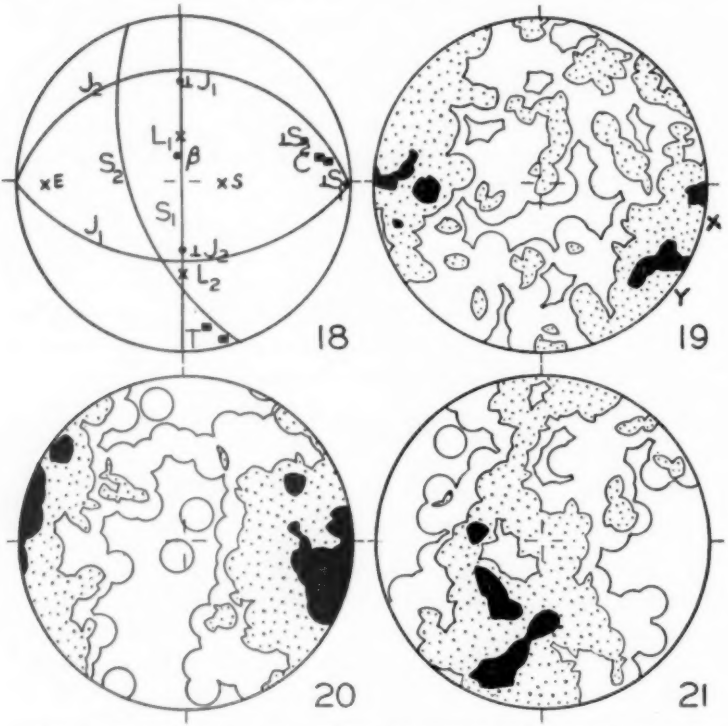
Under the microscope the rock is seen to be composed mainly of calcite grains 0.5 mm. to 1 mm. in length with distinct elongation parallel to the trace of S_2 or in some cases S_1. Parallel to S_1 are bands less than 0.5 mm. thick composed of much smaller grains of calcite, plentiful small crystals of apatite, and less abundant grains of sphene, micas, albite and pyrite. These bands are assumed to represent relict bedding. Twinning on $\{01\bar{1}2\}$ is conspicuous in much of the coarse calcite.

Investigation of preferred orientation of calcite was confined to the dominant coarse material. Two mutually perpendicular sections, both cut normal to the foliation S_1, were used—the one oriented normal to the strike of S_1, the other being geographically horizontal. Plotted points representing measurements made on the second of these sections were rotated on the

projection net into the plane of the first section. All fabric diagrams therefore are drawn on the plane normal to the strike of S_1, looking towards S20°E.

Preferred orientation of calcite lattice

Orientation of c *axis.*—The optic axis was measured in each of 300 grains—150 grains in each section. Though {01$\bar{1}$2}



Figs. 18-21. Sonora marble, 55M50. Megascopic fabric and orientation of calcite. All diagrams are projected on plane normal to strike of foliation S_1, looking S20°E.

Fig. 18. Foliation S_1, *s*-surfaces S_2, joints J_1, joints J_2, lineation L_1 (in marble), lineation L_2 (in adjacent phyllites). The axis β is transferred from figure 27. S = south; E = east.

Fig. 19. *c* axes of calcite (307 grains measured in two mutually perpendicular sections). Contours at 3%, 1%, 0.3%, per 1% area.

Fig. 20. Poles of most prominent {01$\bar{1}$2} lamellae (1 per grain in 307 grains). Contours at 3%, 1%, 0.3%, per 1% area.

Fig. 21. Edges [*e*:*e'*] between prominent {01$\bar{1}$2} lamellae (291 in 307 grains). Contours at 3%, 1%, 0.3%, per 1% area.

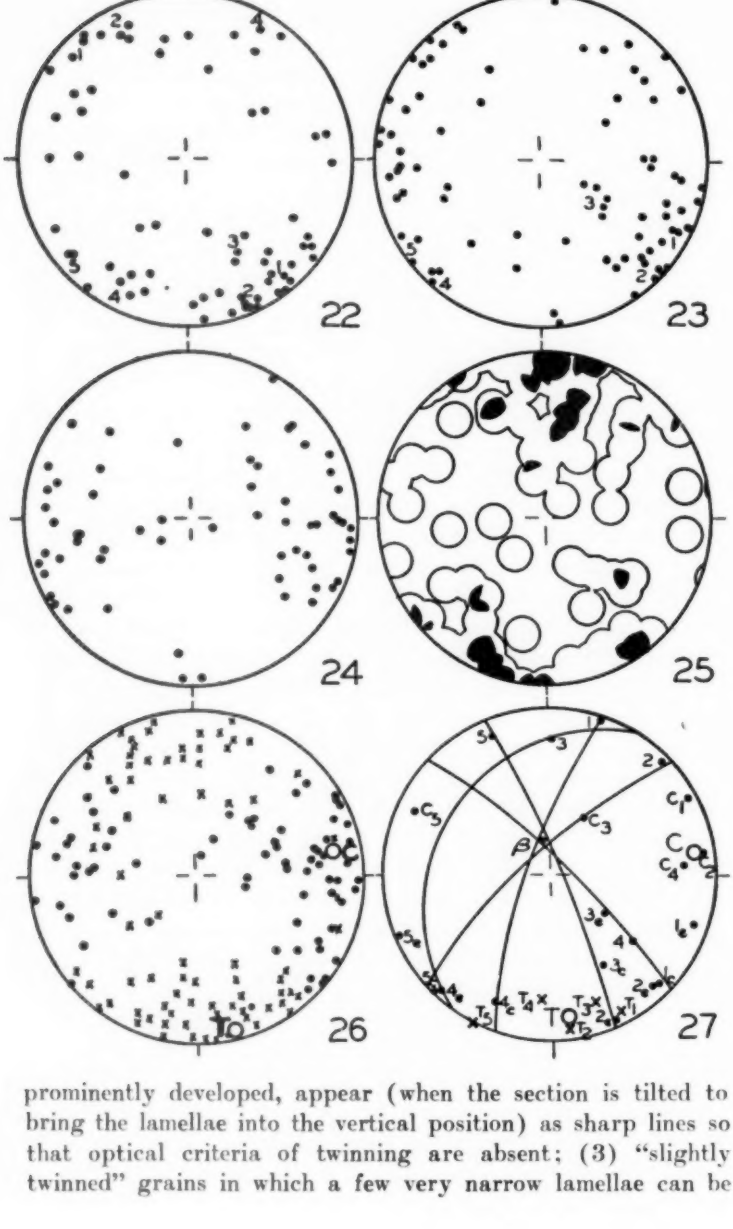
twinning is conspicuous in many grains there is seldom any doubt as to which of the alternative positions of the *c* axis represents the dominant space lattice of any grain. Figure 19 is a collective orientation diagram for *c* axes of 307 grains. The pattern of preferred orientation is weak, but shows three features all of which are obvious in both of the partial diagrams upon which figure 19 is based: (1) a broad area of concentration XY asymmetrically inclined to S_1; (2) within this, a small maximum coinciding with the pole of S_1; (3) an ill-defined zone of minimum concentration of axes parallel to S_1.

Orientation of $\{01\bar{1}2\}$ *lamellae.*—Figure 20 shows preferred orientation of poles of most conspicuous $\{01\bar{1}2\}$ lamellae—309 sets measured in 300 grains. The only persistent feature of the diagram is a broad zone of concentration eccentrically situated with reference to the poles of S_1 and S_2 and overlapping the broad *c*-axis maximum of figure 19.

Orientation of edges $[e{:}e']$.—Preferred orientation of the edge $[e{:}e']$, between the two most prominent sets of $\{01\bar{1}2\}$ lamellae of each grain (fig. 21), is weak except in so far as it is conditioned by the orientation pattern of the *c* axes. From the distribution of these in figure 19 it is clear that all edges of the $[e{:}e']$ type must be concentrated in a broad belt corresponding to that of figure 21. In the Sonora marble one set of $\{01\bar{1}2\}$ lamellae, e_1, is outstandingly prominent in most grains; but the two remaining sets, e_2 and e_3, are clearly developed in many cases, so that selection of the second appropriate lamella for determination of $[e{:}e']$ may be arbitrary. There is a tendency to select from the two weaker sets of lamellae the one which is most nearly perpendicular to the plane of the section. Hence the respective maxima of the two partial diagrams constructed for differently oriented sections do not coincide; in each case the maximum within the broad concentration zone is biased toward the center of the diagram in question regardless of the orientation of the corresponding section.

Orientation phenomena in twinned grains

In both sections the measured grains of calcite may be divided arbitrarily into three equally well-represented groups: (1) grains with optically obvious strong twinning on $\{01\bar{1}2\}$; (2) "untwinned" grains in which all $\{01\bar{1}2\}$ lamellae, even where



prominently developed, appear (when the section is tilted to bring the lamellae into the vertical position) as sharp lines so that optical criteria of twinning are absent; (3) "slightly twinned" grains in which a few very narrow lamellae can be

shown by their optical behavior to be twinned. To evaluate the role of twin gliding in development of $\{01\bar{1}2\}$ lamellae, grains of the first two categories were compared in detail (figs. 22-24). The contrasted distribution of points in figures 22 and 24 demonstrates a close correlation between degree of twinning and orientation of the corresponding space lattice within the rock fabric. Nearly all grains whose *c* axes lie in the vicinity of the points severally numbered 1 to 5 in figure 22 are strongly twinned. By contrast, most grains with *c* axes inclined at high angles to the foliation S_1 are "untwinned." The possibility that grains of the latter category are in fact completely twinned is discussed critically in a later section and is discarded for reasons given there.

As in the two previous marble fabrics described above, the restricted range of orientation of *c* axes in strongly twinned grains suggests that twinning has occurred in response to a simple system of applied stress applied to an aggregate of calcite grains whose lattices were already oriented as shown in figure 19. This possibility finds some support in the rather regular orientation of glide lines $[e{:}r]$ in observed twin lamellae

Figs. 22-27. Sonora marble, 55M50. Orientation of calcite. All diagrams projected on plane normal to strike of foliation S_1 (vertical), looking S20°E.

Fig. 22. *c* axes in 68 grains with strong $\{01\bar{1}2\}$ twin lamellae.

Fig. 23. Poles of $\{01\bar{1}2\}$ twin lamellae (78 in 68 grains). Lamellae falling in numbered areas belong to grains whose *c* axes fall in correspondingly numbered areas of figure 22.

Fig. 24. *c* axes in 63 untwinned grains (out of 150 measured).

Fig. 25. Glide lines $(01\bar{1}2){:}(10\bar{1}1)$ in 68 $\{01\bar{1}2\}$ twin lamellae. Contours at 4.5%, 1.5%, per 1% area.

Fig. 26. Axes of compression (dots) and tension (crosses) most favoring observed twinning on $\{01\bar{1}2\}$ in 68 individual grains. C and T are respective centers of concentration of compression and tension axes.

Fig. 27. Twinning in groups of grains numbered in figures 22 and 23: 1_c, 2_c, etc., are centers of *c* axis groups of figure 22. 1_p, 2_p, etc., are centers of corresponding groups of twin-lamella poles in figure 23. C_1, C_2 . . . . T_1, T_2, etc., are axes of compression and tension deduced from corresponding groups of *c* axes and twin lamellae; C and T are weighted centers of these stress-axes groups. The five arcs represent the statistical slip planes of the fabric whose poles are 1_p, 2_p, etc.; the numbered points 1, 2, etc., in these arcs are glide lines of the $(01\bar{1}2){:}(10\bar{1}1)$ type within these slip planes. β is the common intersection of four slip planes.

(fig. 25). It is strengthened greatly by the regular grouping of compression and tension axes most favorable to twinning, as determined graphically for individual twinned grains. These lie close to C and T, respectively, in figure 26.

Since the spread of *c* axes in twinned grains is greater than in the case of the other two marble fabrics described above, C and T have also been determined alternatively by somewhat different means. Take a group of *c* axes of generally similar orientation—e.g., points in the vicinity of 1 in figure 22.[1] Plot poles of observed $\{01\bar{1}2\}$ twin lamellae for all grains in the group. The lamella poles likewise are found to fall into a restricted area the center of which is about 26° from that of the *c*-axis group. Now determine graphically a compression and a tension axis appropriate for the whole group of grains (using the center of each group as the basis of construction). Centers of *c*-axis and lamella groups and corresponding tension and compression axes for the five numbered sectors of figure 22 are reproduced in figure 27. Centers of the resultant tension-axis and compression-axis concentrations (T and C) were determined taking into account the relative importance of each of the five groups. They closely approximate the corresponding axes C and T (determined by contouring) in figure 26. The great circles of figure 27 represent the five mean attitudes of $\{01\bar{1}2\}$ twin lamellae corresponding to the lamella concentrations numbered 1_c to 5_c. They can be regarded as five statistically defined discontinuous slip surfaces of the marble fabric. Mutual intersections of the four most important of these surfaces almost coincide at the point β, which has the same general significance as have β-axes determined by intersection of megascopic slip surfaces by the method of Sander (1948, p. 138). The existence of a β-axis of common intersection implies common origin of the slip surfaces in question (1, 2, 4, 5) under stresses applied at right angles to β. In all, 70 per cent of the measured strongly twinned grains have *c* axes and twin lamellae falling within the areas of concentration respectively designated 1_c, 2_c, 4_c, 5_c and 1_e, 2_e, 4_e, 5_e in figure 27. Mean glide directions (1, 2, 4, 5 in figure 27)

[1] The numbered areas of figure 22 are marked both by concentration of *c* axes of twinned grains and by absence of axes of "untwinned" grains. Three-quarters of the total axis points of figure 22 fall into the five areas selected.

for the four mean slip surfaces have been determined just as for individual twin lamellae. They are inclined to β at angles of $70° \pm 8°$.

Dynamic interpretation of twin lamellae

All of the data recorded for strongly twinned grains (figs. 22-27) can be explained by assuming simultaneous application of a compressional force in the general direction C and a tensile force approximating to T of figure 27. The assumed compression is nearly normal and the tension almost parallel to S_2. Now S_2 is essentially a plane of parallel elongation and slight displacement of calcite grains. In this respect, and in its relation to deduced compressive and tensile forces, it is reminiscent of the plane of rolling of a rolled metal fabric (Barrett, 1943, p. 406; McGeary and Lustman, 1950, pp. 6, 11); but in the Sonora marble the degree of "rolling" would be relatively slight.

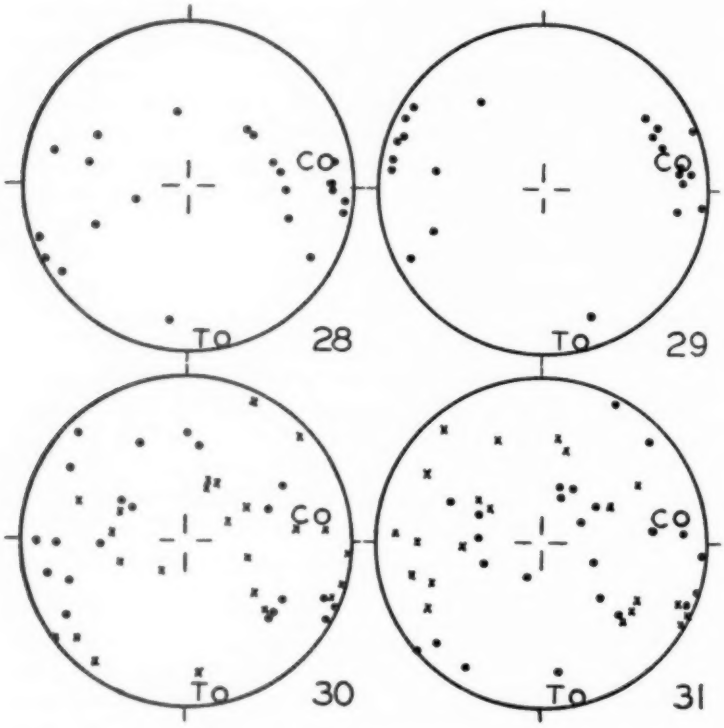
Geographically the deformation deduced from the twin-lamella fabric of Sonora marble may be described as a mild rolling out, under more or less lateral compression, on a plane dipping SW at 70°, with resultant extension of the rolled material approximately in the direction of dip. It cannot be correlated with the earlier and more important deformation responsible for the main foliation S_1.

Dynamic significance of untwinned grains

A scatter diagram for *c* axes in a random sample of untwinned grains is given in figure 28, and the poles of most prominent sets of $\{01\bar{1}2\}$ lamellae (one per grain) in the same grains are plotted in figure 29. In both diagrams the poles are clustered around C, the axis of compression deduced from the data referring to twinned grains. By analogy with the orientation data recorded for *c* axes and $\{01\bar{1}2\}$ lamellae in marble specimens deformed in the laboratory (Griggs, Turner, Borg and Sosoka, 1951, p. 1398), two alternative interpretations of figures 28 and 29 are possible: (1) the untwinned grains in the Sonora marble have failed to twin because their lattices are unfavorably situated within the stress field (Handin and Griggs, 1951, pp. 866-869); or (2) the *c* axes of figure 28 belong to lattices that have become completely twinned during deformation of the marble.

Two lines of evidence collectively support the first of these alternatives and render the second highly improbable:

(1) If the grains of figure 28 were completely twinned, we should expect to find other grains of similar orientation with strong lamellar twinning still recognizable. A glance at figures



Figs. 28-31. Sonora marble, 55M50. Orientation of calcite in a random sample of 22 untwinned grains (out of 79 measured). All diagrams projected on plane normal to strike of foliation S_1 (vertical), looking S20°E. C and T are compression and tension axes of figure 26.

Fig. 28. *c* axes.

Fig. 29. Poles of prominent {01$\bar{1}$2} lamellae (1 per grain).

Fig. 30. Compression axes (dots) and tension axes (crosses) most favoring twinning on {01$\bar{1}$2} lamellae of figure 29, assuming grains are essentially untwinned.

Fig. 31. Compression axes (dots) and tension axes (crosses) most favoring twinning on {01$\bar{1}$2} lamellae of figure 29, assuming grains are completely twinned.

22 and 24 shows that this is not the case: twinned and untwinned grains differ sharply in orientation.

(2) Assuming that the grains shown in figure 28 have become completely twinned on corresponding $\{01\bar{1}2\}$ lamellae recorded in figure 29, it is possible to construct graphically the original *c* axis of each grain, and then to determine the positions of the respective axes of compression and of tension that would be most effective in bringing about the assumed twinning. The compression and tension axes so determined are reproduced in figure 31. Not only do these show little regularity in their orientation, but there is no correlation between their distribution and the directions of compression and tension deduced from the partially twinned grains. If we are indeed concerned with completely twinned grains, then we must assume that the forces that brought about this twinning were directed at random and were in no way related to the uniformly directed forces responsible for partial twinning of other grains.

Finally there is the question of what dynamic significance may be attached to the prominent $\{01\bar{1}2\}$ lamellae observed in most untwinned grains. Do they represent incipient twinning, or are they products of some other mechanism of deformation? In figure 30 are plotted compression and tension axes favoring twinning on individual lamellae of figure 29, assuming that the grains are otherwise untwinned (i.e., that *c* axes of figure 28 are "original"). The points of figure 30 are so irregularly scattered and so little related to the corresponding points of figure 26 (twinned grains) that it is difficult to regard the linear lamellae of the untwinned grains as due to incipient twinning of the same kind as has given rise to strong lamellar twinning in twinned grains. Moreover the striking tendency for the lamella poles of figure 29 to cluster round the previously assumed compression axis C shows that these lamellae would be planes of low resolved shear stress under such compression, and so should be incapable of twinning. Why such visible lamellae develop on planes of low shear stress is still not understood. But it has been shown beyond doubt that in marble cylinders compressed or extended in such a direction that most grains are unfavorably oriented for twinning, linear lamellae similar to those of our present untwinned grains appear in greatest profusion on those $\{01\bar{1}2\}$ planes for which the resolved shear stress in the glide

direction [*e*:*r*] approaches zero (Turner and Ch'ih, 1951, p. 899, fig. 6, no. 154).

It is concluded that the "untwinned" grains of the Sonora marble are in fact untwinned, and that the linear {01$\bar{1}$2} lamellae observed in them have developed under the same system of applied stress as was responsible for appearance of recognizable twinning in other grains.

CONCLUSIONS

(1) Many coarsely crystalline marbles lack obviously cataclastic structure and are remarkably homogeneous as regards preferred orientation of the *c* crystal axis of the calcite lattice. Careful measurement of 100 typical grains is sufficient to bring out the significant details of such a fabric, and serve as a basis for its dynamic interpretation in the light of what is known of the fabrics of experimentally deformed marbles.

(2) The preferred orientation pattern for *c* axes reflects that phase of metamorphism in which the grains assumed their present shape and size. In some cases, e.g., Yule marble described in this paper, the *c*-axis diagram is dominated by a concentration of axes at high angles to a foliation defined by parallel alignment of lenticular grains. Experiment shows that a similar concentration of *c* axes develops parallel to an axis of compression in marble deformed at temperatures of 300°C. or less. The natural fabric may be interpreted tentatively as having developed during compression normal to the foliation. But such an interpretation neglects the possible influence of recrystallization which undoubtedly played an important role in metamorphism but which took little or no part in the process of experimental deformation. To the writer it seems probable that the main effect of recrystallization synchronous with deformation is somewhat to weaken an orientation pattern which would otherwise have developed to a higher degree by purely mechanical processes (twin gliding, translation gliding, rotation of grains, and so on). This view, admittedly speculative, is based on the rather weak concentrations of *c* axes in many well-foliated marbles, as contrasted with stronger concentrations achieved in marble cylinders shortened by 30 per cent or less in the laboratory.

(3) Visible lamellae in all marbles described in this paper are almost exclusively parallel to {01$\bar{1}$2} of the calcite lattice.

Some grains show a superficially similar lamellar parting parallel to a $\{10\bar{1}1\}$ face. Lamellae of other crystallographic orientations have been searched for, but are absent.

(4) The *c* axes and the $\{01\bar{1}2\}$ lamellae of grains with optically recognizable $\{01\bar{1}2\}$ twins have a restricted range of orientation as compared with the range of the same crystal elements for twinned and untwinned grains of the same rock considered collectively. This restricted range of orientation for twinned grains may be explained on the assumption that twinning developed in the last stages of deformation under a simple system of applied stress. The nature of this stress is readily deduced from consideration of orientation data referring to twinned crystals.

(5) Grains whose lamellae are not optically recognizable as twins are in most cases untwinned rather than completely twinned crystals with reference to post-crystalline deformation. The visible $\{01\bar{1}2\}$ lamellae within them may be correlated with the same stress system as was effective in causing twinning in other grains. The most prominent sets of $\{01\bar{1}2\}$ lamellae of untwinned grains are aligned at high angles to the deduced direction of compression, i.e., in planes of low shear stress.

(6) The direction and nature of late applied stress deduced from twinning hold good within a hand specimen. Whether they may remain constant over larger fields has not yet been tested. Further investigation of this phase of the problem by D. B. McIntyre and the writer is now in progress.

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Department of Geological Sciences
University of California
Berkeley, California

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A NOTE ON THE STABILITY OF JADEITE

LEASON H. ADAMS

ABSTRACT. By the use of certain simplifying assumptions the stability pressure, at various temperatures, for the formation of jadeite from nepheline and albite is calculated from thermal data. The pressure increases by about 18 bars per degree; and at 400° C. the pressure is estimated to be 4800 bars. From the known behavior of hydrates under high pressure it is suggested that under pressure analcite may melt incongruently to form jadeite and water, so that at a sufficiently high pressure jadeite rather than analcite would be produced from a mixture of the correct composition, even in presence of excess water.

THE EFFECT OF PRESSURE ON STABILITY

ONE of the comparatively rare minerals is jadeite, which is a hard, dense material having a composition that is represented by the formula $Na_2O \cdot Al_2O_3 \cdot 4SiO_2$ with varying amounts of diopside and other substances in solid solution. It is of especial interest because it has never been synthesized, despite much effort on the part of numerous investigators to accomplish this. One of the earliest attempts, which was inconclusive, was by Professor Pentti Eskola and the writer when the former was a guest investigator at the Geophysical Laboratory about twenty-five years ago. When natural jadeite is heated it begins to decompose at temperatures as low as 800° C., first forming a certain amount of glass (Greig and Barth, 1938) and then recrystallizing to a mixture of nepheline ($Na_2O \cdot Al_2O_3 \cdot 2SiO_2$) and albite ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$). Glass of jadeite composition, when held at 900° or 1000° crystallizes into nepheline and albite, but at 800° or lower the material seems to persist indefinitely as glass (Yoder, 1950). As reported by Yoder, the unpublished work of Morey and of Bowen and Tuttle shows that with a mixture of the composition of jadeite in the presence of water vapor at a pressure of 1000 or 2000 atmospheres and at temperatures of 600° to 700° nepheline and albite are produced, while at temperatures of 400° to 550° the hydrated compound analcite, $Na_2O \cdot Al_2O_3 \cdot 4SiO_2 \cdot 2H_2O$, forms promptly. Further experimental work by Yoder (1950) at pressures extending to somewhat more than 2000 bars yielded a definite pressure-temperature curve for the decomposition of analcite into nepheline plus

albite plus water. The equilibrium pressure increases rapidly with temperature, the relation being approximately linear, except possibly at the lower pressures. Representative points on the line are 500 bars at 538° and 2000 bars at 563°.

If we consider the reaction

$$\tfrac{1}{2}\ \mathrm{Ne} + \tfrac{1}{2}\ \mathrm{Ab} = \mathrm{Jd} \qquad (1)$$

in which the symbols, in order, stand for nepheline, albite, and jadeite respectively, with the formulas written as above, we note that the reaction proceeds with a diminution of volume. The respective densities of synthetic nepheline, natural albite, and natural jadeite at room temperatures and atmospheric pressure are 2.619, 2.605, and 3.328, from which it is readily calculated that the reaction as written proceeds with a volume change of -33.4 cm^3. It is a well known principle of thermodynamics that high pressure favors the formation of dense materials. If, for example, a substance such as jadeite is unstable at atmospheric pressure with respect to nepheline and albite (which definitely seems to be the case at high temperatures), then, without knowing any properties of the materials except their densities or specific volumes, we may be sure that at a sufficiently high pressure jadeite will be the stable form at the temperature to which the measurements pertain. Quantitatively, the situation may be described by the well known equation

$$\delta\ (\Delta\ F) = \Delta\ V\ \delta\ P \qquad (2)$$

in which $\Delta\ F$ is the free energy for the reaction, $\Delta\ V$ is the volume change, and P the pressure. The equation states that the variation in the free energy change is equal to the difference in volume of the products and the reactants multiplied by the variation in pressure. This relation is important because if the product of the reaction does not tend to form spontaneously at ordinary pressures—that is to say, if the product is unstable and thus $\Delta\ F$ for the reaction is positive—then in the event that $\Delta\ V$ is negative (i.e., the reaction proceeds with a decrease in volume), we may readily calculate from $\Delta\ V$ and $\Delta\ F$ the pressure required to reduce the positive $\Delta\ F$ to zero or beyond—the fundamental condition of thermodynamic stability.

There are now data at hand from which, by application of the principle stated above, we can draw useful conclusions as to the stability of jadeite not merely at room temperature but

also, as we shall see later, at those higher temperatures that are known to be favorable to mineral formation. To determine ΔF at atmospheric pressure we use the well known relation

$$\Delta F = \Delta H - T\Delta S \qquad (3)$$

in which ΔH is the enthalpy difference, i.e., the negative of the heat of reaction as ordinarily defined, T is the temperature on the absolute scale, and ΔS the entropy difference. By averaging the results obtained by Kracek, Neuvonen, and Burley (1951) for the reaction heat determined from the heats of solution of various samples of the pertinent minerals in hydrofluoric acid, we find that ΔH is -6120 calories at 25° C. The entropy may be determined by measuring the heat capacities (i.e., specific heats) down to temperatures close to absolute zero. From the unpublished measurements of Kelly and Todd, quoted by Kracek, Neuvonen, and Burley (1951), it is found that ΔS for the reaction (1) is -14.7 cal/deg at 25° or 298° K. It follows that $T\Delta S$ is -4380 cal at 298° K; and that, by equation (3), ΔF is -1740 cal at 289° K. The negative sign means that jadeite is stable with respect to nepheline and albite *at room temperature*, but of course we want to know about ΔF at elevated temperatures.

THE EFFECT OF TEMPERATURE

The variation of ΔF with T may be expressed in several ways. A useful relation is as follows:

$$\mathrm{d}(\Delta F)/\mathrm{d}T = -\Delta S. \qquad (4)$$

In the limiting case for which ΔC_p, the difference in heat capacities of the products and reactants, is zero, ΔS, being dependent on ΔC_p, is constant; and by integration we obtain immediately the simple form

$$\Delta F = \Delta H + IT \qquad (5)$$

in which I is a constant. It should be carefully noted that equation (5) is to be used *only in the temperature for which* $\Delta C_p = 0$. In this particular case I is equal to $-\Delta S$, which is constant because ΔC_p is assumed to vanish for the particular range of temperature throughout which equation (5) is applicable. (Of course, in general, and especially at temperatures below room temperature, ΔC_p may be very far from zero, and ΔS may thus be very far from being constant.)

If ΔC_p is finite but constant, the variation of ΔF with T takes the familiar form

$$\Delta F = \Delta H_0 - \Delta C_p \ln T - IT \qquad (6)$$

in which ΔH_0 may be considered to be a constant determined by the equation

$$\Delta H = \Delta H_0 + T\Delta C_p \qquad (7)$$

which expresses the variation of ΔH with T through the temperature range for which ΔC_p is constant. Equation (6) applies *only* to that same temperature range.

The value of these simplified expressions for the problem in hand will become apparent when we tabulate, as is done in

TABLE 1

ΔC_p for the Reaction ½ Ne + ½ Ab = Jd (Kelly and Todd)

T	Cp(cal/deg) ½ Ne	½ Ab	Jd	ΔC_p
50	4.56	7.80	5.10	−7.26
75	8.35	13.74	13.10	−8.99
100	11.74	19.31	22.68	−8.37
125	14.80	24.52	32.40	−6.92
150	17.46	29.22	41.28	−5.40
175	19.86	33.46	49.02	−4.30
200	21.98	37.26	55.86	−3.38
225	23.88	40.26	62.10	−2.04
250	25.60	43.74	67.62	−1.72
275	27.14	46.52	72.54	−1.12
298	28.38	48.96	76.68	−0.66

table 1, the unpublished results obtained by Kelly and Todd (mentioned above) for the heat capacities of nepheline, albite, and jadeite. It is evident that ΔC_p decreases numerically with increasing T, reaching the low value, −0.66 cal., at room temperature. A reasonable assumption is that ΔC_p is becoming assymptotic to zero and then maintains that value at higher temperatures. This assumption would be equivalent to the assertion that at high temperatures the molecular heat capacities of the silicates under consideration are additive functions of the atomic properties, there being, of course, the same assemblages of atoms on the two sides of equation (1).

Utilizing this assumption that at the higher temperatures ΔC_p is 0, we apply equation (5), noting that $\Delta H = -6120$

cal., $T\Delta S = -4380$, $(\Delta F)_{298} = -1740$, from which it is readily found that $I = 14.7$; and we calculate ΔF for the basic reaction at various temperatures up to $T = 900°$. It turns out that ΔF steadily increases (algebraically), reaching a value of several thousand calories (positive) at the upper end of this temperature range. At the higher temperatures, therefore, jadeite is unstable unless a certain amount of pressure is applied. To calculate this pressure for each temperature, we turn to equation (2), noting that in this equation, if ΔV is in

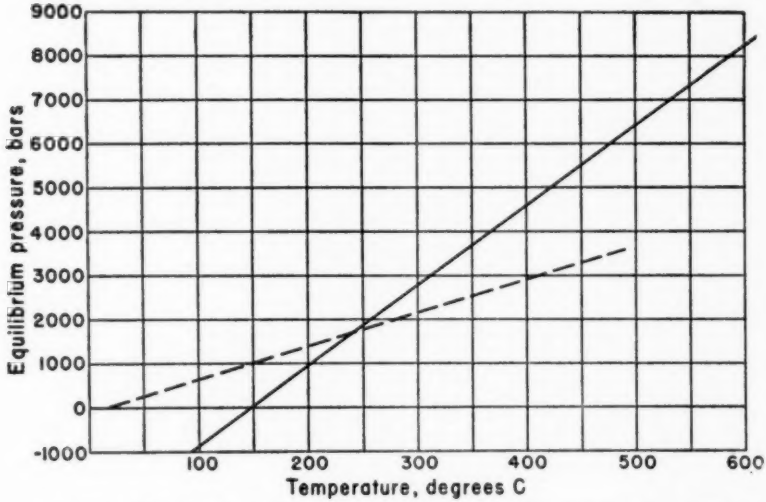

Fig. 1. The solid line shows, as a function of temperature, the equilibrium pressure for the formation of jadeite from nepheline and albite. Temperatures in the Earth corresponding to a gradient of 35 deg/km and a crustal density of 2.7 are given by the dashed line.

cm^3 and P is in bars, ΔF will be in decijoules. In order to convert calories to decijoules we multiply by 41.84; and one practical form of equation (2) is therefore

$$P = -41.84\ (\Delta F)/\Delta V \qquad (2a)$$

in which P, the pressure required to reduce the positive ΔF to zero, is expressed in bars, ΔF is in calories, and ΔV in cm^{-3}. Finally, because ΔV is -33.4 cm^3, we simply multiply the (positive) values of ΔF obtained from equation (5) by 1.25 to obtain the equilibrium pressures (in bars) at the various temperatures.

These equilibrium pressures are plotted against temperature in figure 1. The most interesting range is from 400° C. to 600°. At lower temperatures mineral formation is usually sluggish, and at higher temperatures improbably high pressures would be required. It may be seen from the curve that at 400°, 500°, and 600° C. the equilibrium pressures are respectively 4700, 6500, and 8300 bars.

It is interesting to calculate the differences in the results that would be obtained if ΔC_p should have a high temperature value, — 0.5, rather than zero. In this case equation (6) is applicable. With $\Delta C_p = -0.5$, ΔH_0 is — 5970, and I is found to be 11.2. (Note that I is no longer to be identified with $-\Delta S$.) At 400° C. this equation yields a value of P about 100 bars higher than is obtained on the assumption that ΔC_p equals zero—an insignificant difference.

Similar considerations permit the calculation of the stability pressure for the formation of one formula weight (as here defined) of jadeite and two formula weights of quartz from one formula weight of albite at various temperatures. Here again, ΔC_p seems to be practically zero at room temperature and above; and ΔV is nearly the same as before, namely — 34.4 cm^3. Taking — 1210 cal. as the average of Kracek, Neuvonen and Burley's results for ΔH and — 4420 from Kelly's results for $T\Delta S$ at 25°, we may readily calculate that the stability pressures at 300° and 400° are respectively about 9000 and 10,800 bars.

EFFECTS OF COMPRESSIBILITY AND EXPANSIBILITY

It is obvious that strictly the proper volumes to use in the thermodynamic relation are those pertaining to the equilibrium pressures and temperatures. The effects of compressibility and thermal expansibility have been studied by Yoder and Weir (1951) using their own data on compression and the unpublished data by J. L. Rosenholtz and D. T. Smith on thermal expansion. From the equation of Yoder and Weir showing the combined effect of temperature and pressure on the volume change of the reaction in equation (1), it may be seen that this effect is not very important—as recognized by Yoder and Weir. As an example, a pressure of 5000 bars causes the volume change at room temperature to decrease numerically by 1.1, that is, from — 33.4 to — 32.3; and an increase of tempera-

ture from 25° C. to 400° C. at atmospheric pressure causes the volume change to increase numerically by 1.0. The two effects thus tend to offset each other. Because of this, since the compressibility of the pertinent minerals is still not known at high temperatures (or, what amounts to the same thing, the thermal expansibility at high pressures), and because of the apparently inevitable uncertainties in the basic thermal measurements leading to ΔH, ΔS, and ΔF, it thus appears that at present the effects of compressibility and expansibility can be ignored for the purposes of solving the jadeite problem. Similarly, as indicated above, the high-temperature heat capacities seem to be unimportant in this connection. Rather, for progress in the final solution of the problem, experimental effort should be concentrated on attempts to synthesize jadeite at higher pressures than have yet been tried, and perhaps also on improving somewhat the accuracy of measurements leading to the heat of reaction.

HYDRATES UNDER PRESSURE

As mentioned above, when a mixture of jadeite composition is heated under pressure and in the presence of water, the hydrate analcite is formed at pressures above the equilibrium pressure corresponding to the particular temperature (e.g. 2000 bars at 538°); and at lower pressures a mixture of nepheline and albite is produced. Analcite, thus, appears to form whenever sufficient water to produce the hydrate is present and when the proper pressure is applied. This circumstance has raised serious doubts among some investigators as to whether jadeite can ever be synthesized except with a deficiency of water. If Yoder's curve for the decomposition of analcite is plotted in the same diagram with the curve of figure 1, it may be seen that the two curves (extrapolated) cross at about 650° and 9000 bars. Accordingly, it might seem that except at very high pressures the analcite curve is the significant one.

In this connection it is interesting to consider the effect of pressure on hydrates. This subject was discussed by Adams (1938) and it was shown that, depending on circumstances, a hydrate subjected to pressure may melt, or the appropriate solution under high pressure may solidify to a hydrate. Figures 3 and 6 in the contribution cited illustrate the general appearance of the equilibrium curves for various types of congruent

and incongruent melting at constant temperature and variable pressure, and figure 5 of that paper, which is the actual equilibrium diagram for the system Na_2SO_4—H_2O, shows the incongruent melting of $Na_2SO_4 \cdot 10H_2O$ at 4600 bars and 25°.

Such a melting under pressure will usually take place when the products (solution plus anhydrous material) have a lower agregate volume than the hydrate. Now let us consider the reaction

$$\text{Analcite} = \text{Jadeite} + 2H_2O. \qquad (8)$$

If the reaction proceeds with a diminution in volume, then pressure should favor it. It is difficult to estimate precisely the volume change in the most interesting region of temperature and pressure, but from the density at room temperature of analcite (2.285) and from an extrapolation of the curves presented by Kennedy (1950) for the specific volume of water at elevated temperatures and pressures, it is probable that at 4000 bars and at 400°, 500° and 600° the volume changes are respectively -30 cm^3, -27 cm^3, and -23 cm^3 for the reaction as written. The circumstance that these values of ΔV are strongly negative suggests that at pressures no higher than the equilibrium pressures (as shown in figure 1 for the formation of jadeite from nepheline and albite) analcite would melt incongruently to form jadeite and water or jadeite plus a saturated solution. (For temperatures above the critical point of water some persons might prefer to call such a process *incongruent sublimation.*) Thus even with excess water a mixture under a sufficiently high pressure might form jadeite rather than analcite. To determine the transition pressure by the thermodynamic method, it would be sufficient to know, in addition to the information already in hand, the thermal properties of analcite and (probably) also the specific volume of water, in the range from 400° to 600°, at somewhat higher pressures than have been applied previously to such experimentation.

CONCLUDING REMARKS

In figure 1 the temperatures in the crust of the Earth corresponding to a thermal gradient of 35 deg/km and a rock density of 2.7 are shown by the dashed line. It may be seen that this line crosses at about 240° the line for the equilibrium pressure of jadeite formation from nepheline and albite, and

that at the higher temperatures the pressures given by this line are below the equilibrium pressures. Therefore, with what may be called a normal temperature gradient the pressures are apparently not high enough, in the range of temperature favorable to mineral growth, for jadeite to be stable. If figure 1 gives a true picture of the equilibrium conditions for the formation of jadeite under anhydrous conditions, and if the temperature gradient is "normal," then we should be obliged to conclude that only at temperatures below 240° could jadeite be stable. It should be noted, however, that there is unfortunately an uncertainty of considerable amount in the measured heat of reaction, one of the principal factors used in the calculation of the stability pressure. The measurement of the heats of solution of silicates in hot hydrofluoric acid involves many experimental difficulties; and it is therefore not surprising that the results of measurement show a spread that indicates that the average for the heat of reaction may be in error by several hundred calories, corresponding to perhaps a thousand bars. Furthermore, the thermal gradient in the Earth's crust is known to vary over a wide range. In some regions the gradient is much smaller than 35 deg/km, and in others larger. If the gradient were as low as 22 deg/km, then the pressures corresponding to given temperatures would be sufficiently high for the line expressing temperature as a function of pressure in the Earth to cross the jadeite equilibrium-pressure line of figure 1 at 400°; and at this temperature or below and at depths of about 17 km or less, jadeite would be stable.

We may conclude either (1) that the temperature gradient in regions where jadeite is found is lower than normal (or alternatively that the value taken for the heat of reaction should be numerically higher); or (2) that jadeite has been produced in the Earth as an unstable phase and has persisted unchanged despite the insufficient pressure in comparison with the pressure required for stability.

Finally, it is suggested that further attempts at synthesis in the presence of water and at pressures higher than have been used heretofore for this purpose would be worth while.

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Geophysical Laboratory
Carnegie Institution of Washington
Washington, D. C.

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COMMUNICATION

THE PREORBITAL FOSSA OF HIPPARION

The significance of the preorbital fossa in the Equidae, and in *Hipparion* in particular, has often been discussed. Gaudry (1863) made it the site of a "larmier." Lydekker (1884) considered the cavity to be homologous to that which houses the facial gland in the artiodactyls. Gregory (1920*a*, *b*) seemed to rule out all other suppositions when he showed that none of them rests on any concrete evidence. According to him, neither a gland nor a muscle was situated in the preorbital fossa of the extinct Equidae; he regarded the fossa as accommodating a diverticulum nasi analogous to that observed in *E. grevevi*.

The following remarks bear on Gregory's hypothesis:

1. Gregory states that the "larmier" of the ruminants and oreodonts is "more or less circular in form and bounded by a well defined rim" (Gregory, 1920*b*). Specimens of Recent gazelles and cephalophines were examined at the British Museum (London) and it was found that the front margin of the fossa is not at all well defined but dies out smoothly forward and downward as it does in many Equidae. On the other hand, many specimens of *Hipparion* and other Equidae show a fossa in which the anterior rim is well defined. Gregory himself shows examples of this in his plate 18.

2. In *E. grevevi*, there is no such definite fossa as in *Hipparion*. Only a shallow groove is observable and it usually extends along the facial surface of the premaxilla, maxilla, and nasals. This groove lies between the infraorbital foramen and the margin of the anterior nares and close to the latter, whereas in *Hipparion* it lies much farther back, usually behind the infraorbital foramen, near the lacrymal, and it forms a shallow pit. The distance between the posterior notch of the nares and the fossa varies, in *Hipparion*, between 40 and 65 mm and the intervening space is occupied by the flat surface of the maxilla. The diverticulum nasi must have been contained in

a narrow space between the bone and the superficial muscle as it passed back to the fossa.

3. Gregory's hypothesis appears to be the only one which rests on a careful observation of a large number of Equidae. It is probably correct, in the form given by that author, so far as the later members of the family are concerned. It is however probable that, where the preorbital fossa is a definite pit, the blind end of the diverticulum contained a solid or semi-solid substance of a fatty or mucous nature.

4. The existence of a canal opening into the posterior pocket of the fossa has often been discussed. It has been denied by some authors. Sefve (1927) made a section of a skull of *Hipparion* and said he found a separate canal which was quite distinct from the infraorbital canal. The blood and nerve supply for the diverticulum passes through the infraorbital canal and therefore the preorbital fossa should, in Sefve's hypothesis, belong to a system distinct altogether from the diverticulum. Sefve also supposed that the canal of the fossa contained branches of the sphenopalatine nerve and artery. Unfortunately, nothing can be seen clearly on Sefve's picture of the section of the skull.

According to Sisson (1947), the sphenopalatine artery (medial branch) supplies the septum nasi of the horse. It branches from the internal maxillary artery in the pterygopalatine fossa but it may also arise from the infraorbital artery which is another branch of the internal maxillary. On the other hand, the diverticulum nasi is innervated by the external nasal branch of the infraorbital nerve which emerges through the infraorbital foramen. It seems that the diverticulum is also supplied in part from the infraorbital foramen.

Observations on *Hipparion* have shown (a) that there may or may not be a canal in the posterior pocket of the fossa, and (b) that the infraorbital foramen sometimes does not appear. In other words, as far as one can see, the pocket of the fossa may lead into a blind passage of varying depth or into a canal which appears to go downward and inward in the direction of the maxillary foramen. The infraorbital foramen may be seen outside or somewhat inside the fossa, or may be invisible. It cannot be said with certainty from the material at hand that the canal of the fossa exists only when the infraorbital

foramen does not and vice versa, but this is quite possible. In any case, it is worth noting that, when there is no proper infraorbital foramen but a canal through the posterior pocket of the fossa, the situation is analogous to that in *E. greveyi*. Then the fossa lies between the nostrils and the canal of the pocket which is obviously equivalent to the infraorbital canal. The difference between *Hipparion* and *E. greveyi* is merely that there is a greater distance between the nares and the fossa in the former than in the latter. In both animals, the maxilla only is involved, whereas the fossa is placed almost entirely in the lacrymal "in all deer and most antilopes" (Lydekker, 1884).

It is therefore probable that the so-called canal of the fossa is nothing but the infraorbital canal opening more posteriorly than usual. In any case, the blood supply and the innervation of the fossa and diverticulum come from the infraorbital system. It is unnecessary to invoke the intervention of the sphenopalatine artery and nerve, the destination of which is much deeper.

There is little doubt that this system has been variable in the Equidae. *Hipparion* itself may lack the fossa, as in *H. hippidiodus* (Sefve, 1937) and *Proboscihipparion* (ibid.). The position, depth and shape of the fossa also vary a great deal in *Hipparion*. On the other hand, the wall of the maxilla is very susceptible to lateral pressure and is sometimes found to be slightly depressed in modern horses. The development of the fossa is largely an individual character. Having regard to this fact, one may postulate considerable variation in the development of the diverticulum nasi. The preorbital fossa was probably of very little physiological importance to the individual and was likely to be an instable character.

ACKNOWLEDGMENT

This paper is based on observations made in the course of research on the European *Hipparion* offered as a Ph.D. thesis at University College, London. Thanks are due to the authorities of the British Museum for permission to make use of fossil and recent material in the Museum.

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Institut pour la Recherche Scientifique
en Afrique Centrale
Costermansville, Belgian Congo

P. L. Pirlot

ESSAY REVIEW

Morphogenesis. An Essay on Development; by JOHN TYLER BONNER. Pp. vi, 296; 90 figs. Princeton, 1952 (Princeton University Press, $5.00).—This book by John Tyler Bonner, known by his interesting investigations on the slime mold *Dictyostelium discoideum,* is a valuable essay on problems in plant and animal morphogenesis. The arrangement of the subject matter, covering one-celled forms, colonial organisms, and higher forms, is in six sections. These deal with size and pattern, physical and chemical aspects of development, phenomena of polarity and symmetry, patterns of growth, morphogenetic movements, and differentiation. The chapter on growth pattern is the most extensive one; it deals with growth curves, functional adaptation, the structural organizations of varied lower plant and animal forms, meristems, determinate growth in fruits, the role of auxin in growth and dominance, hormones in animals, gradients, and D'Arcy Thompson's Cartesian transformations. Plants and animals are compared, particularly with respect to meristematic growth and hormonal control. The effect of environment on direct functional adaptation in animals is discussed at some length.

In trying to explain the phenomena of development, Dr. Bonner leans most heavily on physico-chemical principles, such as crystal analogies, hormones, and organizers; next come biological concepts, for example, division of labor, functional adaptation, patterns, and regulation; last called upon are organismic, psychological, and philosophical notions, such as organization and *Gestalt.* Development is visualized as consisting of two broad categories: "constructive processes" and "limiting" factors. The former comprise growth, morphogenetic movements, and differentiation; the latter are divided into external ones, such as mechanical stress, size, and food supply, and internal ones, such as hormones, chemical inductors, and gene products. The limiting factors guide the constructive processes and interrelate with them.

Throughout the discussion the principal problem is, of course, the phenomenon of organization. Dr. Bonner prefers to circumscribe this term and mostly speaks of wholeness and regulation. These are implicit in the development of the different unicellular and multicellular plant and animal forms, but apparent also in the ant colony, in patterns of growth, in morphogenetic movements, in polarity phenomena, and in the control of differentiation. It is pointed out that on each of these different levels the mechanisms bringing forth specific forms of wholeness may not be identical. Dr. Bonner's idea, which he states repeatedly, is that the explanation of wholeness or the principle which accounts for orderly, harmonious development must be searched for in terms of a micro-theory dealing with the micro-structure and the spatial configura-

tion of living matter. Here the crystal analogy is especially stressed since the growth, properties, and form of crystals are understandable in terms of smaller repetitive units. The above-mentioned constructive processes and limiting factors lie, according to the author's theory, together in space and time in the germ, forming a configuration of repetitive units which may be the basis for a future theory of micro-structure. But there is no reason to assume that the repetitive units are equivalent in all organisms, and the only certain common denominator in the different forms of organic wholeness is, according to Dr. Bonner, the adaptive significance which lies both in the division of labor and its unity as selective principles in evolution.

Arguments of an epistemological nature enter this book only slightly. To the question whether we are to explain biological phenomena in terms of physics and chemistry of today or tomorrow, the author replies that an explanation in terms of a micro-structure theory will be satisfactory even if not reduced all the way to chemistry and physics. Dr. Bonner expresses his dislike for notions of teleology and purposiveness at one point (page 64) where he takes exception to the concept of directiveness set forth by E. S. Russell. Modern organismic biology has, of course, substituted for the idea of purpose the concept of wholeness. In his discussion of the role of teleology in biology ("The Problem of Knowledge," Yale, 1950), Ernst Cassirer, for example, has pointed out that after the annihilation by Kant of that naive form of metaphysical teleology, that "stranger to natural science," purposiveness reasserted its role as "critical teleology" in scientific description and presentation. With concepts of "fitness," "selection," "survival of the fittest," "selective advantage," which all have a purposive character, the most antiteleological Darwinians became practical teleologists. Whether or not we can entirely free ourselves of the notion of the organism as a basically "teleological structure," we ought to be mindful, at any rate, in our formulations and descriptions of biological behavior, of the nature of teleological pitfalls. There is a bare possibility that some readers may interpret in a teleological sense certain sections (for example, pp. 15, 19, and 101), which deal with the principle of division of labor and with "useful" reactions.

Roux, the great founder of developmental mechanics, did much to further our understanding of the process of "building through functioning," but his name does not appear in index and bibliography. Nor does Voechting's, whose classical theory of plant cell polarity and whose statement that in differentiation "the fate of a cell is a function of its position" make him stand out among early plant morphogeneticists. But this should in no way belittle

the value of the ideas and of the many data provided in this book which cannot be listed here in detail. The volume makes for most agreeable reading, on account of its lively style and its courage of opinion. It is also noteworthy for its fine illustrations and generally excellent layout. ROBERT BLOCH

REVIEWS

A History of the Theories of Aether and Electricity: The Classical Theories; by SIR EDMUND WHITTAKER. Pp. xiv, 434. New York, 1951 (Philosophical Library, $12.00).— For some years Professor Whittaker has been planning a new edition of his celebrated "History of the Theories of Aether and Electricity," published in 1910. Since that date, however, two revolutions have occurred in physics: relativity theory and quantum theory. So now that retirement has provided him with the leisure required to carry out a revision of the original text, the march of time necessitates a more extensive work. The book under review covers the same span of years as the 1910 volume, although with many changes and considerable new material. To come is another volume covering the period from 1910 to the present, which will be awaited with eager anticipation.

The chapter headings follow closely those of the first edition, with the addition of a chapter on "Classical Radiation Theory," the importance of which as a stepping stone on the way to a clearer understanding of the microcosm was not fully appreciated in 1910. As the title indicates, the author's interest is centered on the rise and fall of physical theories. Therefore the experimental discoveries recounted are principally those which led to new speculation regarding the nature of the universe in which we live, or which demanded the rejection of ideas previously nourished.

The first chapter, covering the period extending from the days of Aristotle to the death of Newton in 1727, proceeds rapidly to the age of Descartes, who presented the first detailed concept of an aether. Inductive science was hardly born, and speculation was only beginning to be put to the test of experiment. However, excessive speculation was coming under the control of realists such as Newton and Huygens.

The next period covers the beginning of the sciences of electricity and magnetism. The effluvia of Gilbert gradually gave way to the one-fluid theory of Franklin and to the two-fluid concept of duFay. In the meanwhile Michell and Coulomb were investigating the quantitative laws of attraction and repulsion, in both electrostatics and magnetostatics.

Next the author turns from the aethers postulated to explain electrical and magnetic actions to the luminiferous medium. Here

we pass rapidly from the early ideas to the establishment of the wave character of light by Young and Fresnel. One of the most interesting chapters is that on "The Aether as an Elastic Solid." In it are described the efforts of Cauchy, Green, MacCullagh and Kelvin to devise an elastic medium which would have the properties necessary to account for the experimentally determined characteristics of light. When success was finally achieved by both the rotationally elastic aether of MacCullagh and the labile aether of Cauchy and Kelvin, the mechanics of the medium had become so abstruse that it had lost much of its appeal to the imagination. Furthermore, interest was passing to the electromagnetic theory of light, and soon the relativity theory was to show that the aether concept was more a hindrance than a help to the progress of science.

The names standing out most prominently in the remainder of the book are Faraday, Maxwell, J. J. Thomson and Lorentz. While a whole chapter is devoted to Faraday, Joseph Henry is barely mentioned, and not at all in connection with the discovery of electromagnetic induction. This first volume concludes with the electron theory of Lorentz.

At the end is an index of authors cited, but no subject index.

LEIGH PAGE

Principles of Geochemistry; by BRIAN MASON. Pp. ix, 276; 42 figs. New York, 1952 (John Wiley & Sons, Inc., $5.00).—Dr. Brian Mason of Indiana University has incurred the gratitude of the geological fraternity with his new book *Principles of Geochemistry.* A tremendous amount of information on a great range of topics is compressed into its 276 pages. In these days of increasing specialization in the sciences such versatility as Mason's is indeed rare.

"Geochemistry" today has become a popular catch-all term which can mean any number of things to any number of people, and is only eclipsed in its breadth by the term "geophysics." In its earlier days "geochemistry" was primarily the study of the distribution of the earth's elements. It has been redefined by its practitioners until today little of geology and mineralogy is left outside of geochemistry other than descriptive mineralogy, physiography and structural geology (claimed by geophysics). Mason includes under geochemistry such diverse, but related, topics as the origin of the solar system, temperatures within the earth, a brief treatment of thermodynamics, the structure of silicate crystals, isomorphism and polymorphism in crystals, magmatic differentiation, sedimentation, metamorphism, and a host of only slightly lesser topics.

By such a definition most of genetic geology is included under geochemistry. This reviewer must confess that he too is in sympathy with this definition.

This writer has but one criticism of Mason's excellent book. It could have easily been many times as long. The material in many of

the sections is very much condensed. For example, in the section on thermodynamics, four pages are used to cover the fundamentals of thermodynamics and derive the Clapeyron equation. It seems doubtful that a student with no prior knowledge of thermodynamics could follow this condensed treatment, and, with prior knowledge of thermodynamics such condensed treatment is superfluous. This criticism is lessened, however, for each of the sections in the book is followed by an excellent list of selected references, most of them from the recent literature. An inquiring student can, therefore, start with Mason's general outline of a topic and rapidly work up a general knowledge of his subject.

Mason's book could well be used as a text for an advanced petrology course and should be on the shelves of all petrologists, stratigraphers, and those who consider themselves general geologists.

GEORGE C. KENNEDY

A Concise History of Astronomy; by PETER DOIG, F.R.A.S. Pp. xi, 320. New York, 1951 (Philosophical Library, $4.75).—We have long needed a comprehensive history of astronomy in the English language. The excellent older histories by Grant, Agnes Clerke and Berry leave twentieth century developments untouched. This gap is now filled on a semi-popular level by "A Concise History of Astronomy."

Mr. Doig is the editor of the *Journal of the British Astronomical Association*, and his book is written in much the same spirit as the best parts of that journal. He addresses the general scientific reader and the serious amateur. The attention of teachers of astronomy should be drawn to this very convenient reference for names and dates.

The author has emphasized observational results rather than the history of astronomical ideas. Despite the merits of this plan, great movements which affect many branches of astronomy are thereby obscured. A case in point is the preoccupation of seventeenth and eighteenth century astronomers with improving navigation, and with determining geographical longitude. The long-sustained attack on these two problems greatly stimulated all of the branches of astronomy which offered hope toward their solution: instruments, timekeepers, and the motions of the moon, planets and Jupiter's satellites. The direction taken by eighteenth century astronomy was largely determined by these two goals. Such a synthesis is not brought out in the work under review.

The best parts of Mr. Doig's book are those dealing with astronomy in Britain and during the nineteenth century. The treatment of ancient astronomy contains, unfortunately, an extended account of the apocryphal discoveries by Chinese astronomers in the third millenium B.C. Inclusion of such stories is like beginning a modern history of England with the founding of London by fugitives from the sack of Troy.

There are a hundred pages devoted to the astronomy of the present century. This section is well organized, despite the peculiar difficulties posed to the historian by the bewilderingly rapid and complex proliferation of modern astrophysics. The account of solar observations is excellent, but some less tractable topics like stellar dynamics are dealt with rather briefly.

The great merit of Mr. Doig's book lies in the great wealth of accurate factual information, surprisingly great despite severe space limitations. He should be congratulated on this readable and useful work.

JOSEPH ASHBROOK

The Astronomical Universe; by WASLEY S. KROGDAHL. Pp. xvii, 599; 275 figs. New York, 1952 (The Macmillan Company, $6.25).—This college text is intended primarily for students who take an introductory astronomy course but do not plan to go further. The emphasis is largely on stellar astronomy and astrophysics, reflecting the author's tastes, but classical astronomy is not slighted. The particular attraction of this book lies in a freshness and originality of presentation, both in text and illustrations. There is a wealth of problem material.

One novelty, however, impresses the reviewer as unfortunate, and as partly unfitting the book for serious students. Stellar magnitudes are avoided throughout the book, except in an appendix. Evidently this arose from an over-concession to those students who profess fear of logarithms. This suppression leads to obscurity in the presentation of topics like photometric distances of stars. More important is the handicap needlessly placed upon the better student who wishes to read further in astronomy.

The level of factual accuracy is high, and very few important topics are neglected. A conspicuous exception is the determination of the sun's distance, which could have been treated more fully with much advantage.

The presentation is wholly non-historical, so that the book is nearly free from personal names and dates. This limits the author's opportunities to bring out the connections of astronomy with other cultural areas, which is an important objective for any elementary astronomy course.

An informal literary style has been wisely chosen, but unevenly executed. Usually there is precision and clarity, but occasional descents to an awkward playfulness occur. Not all readers will agree on the suitability of the quotations from Alice in Wonderland and Winnie the Pooh.

Actually "The Astronomical Universe" is one of the best of recent elementary astronomy texts. But its merits could be enhanced by a careful revision before the second edition which it deserves.

JOSEPH ASHBROOK

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